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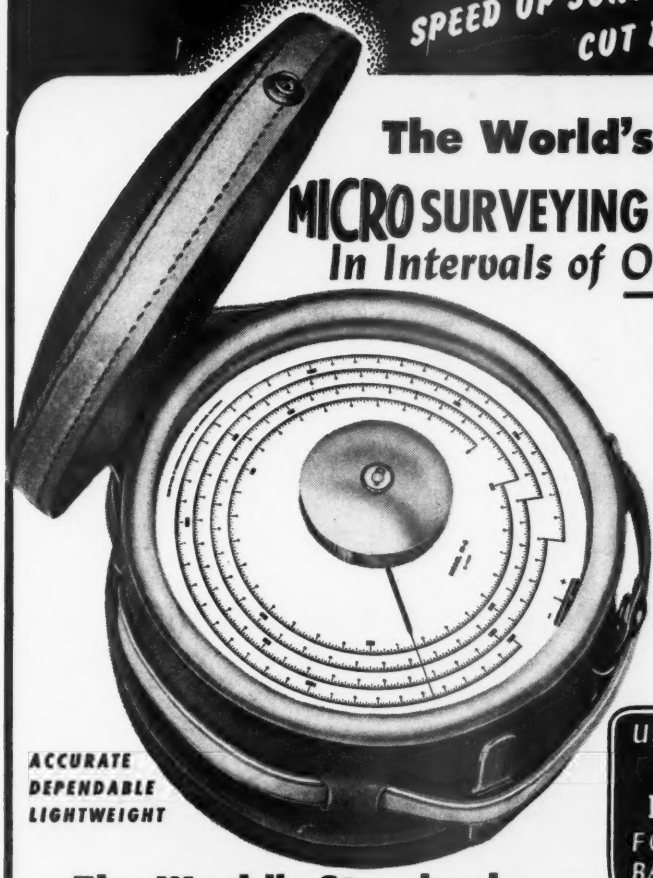

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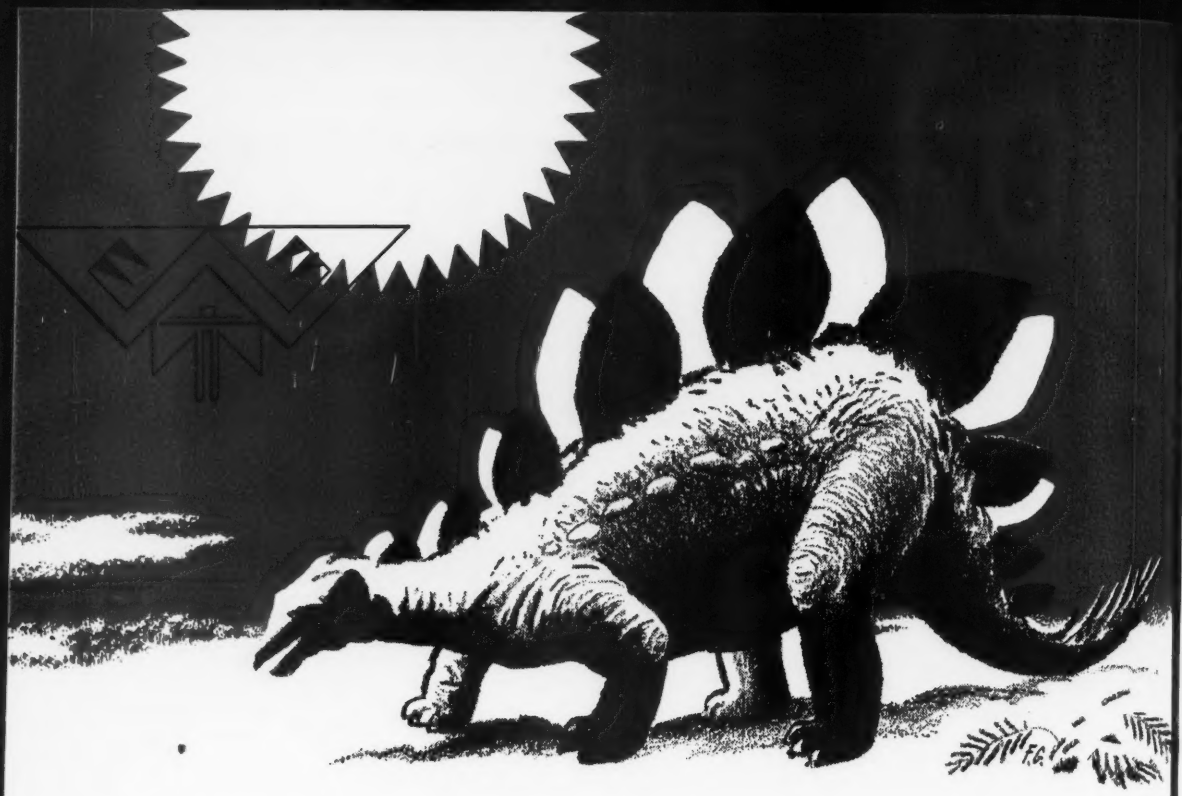

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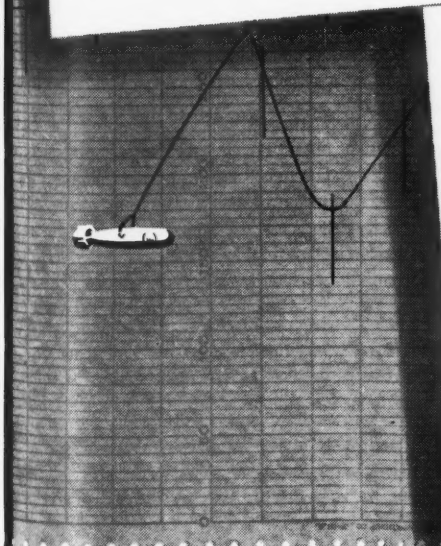

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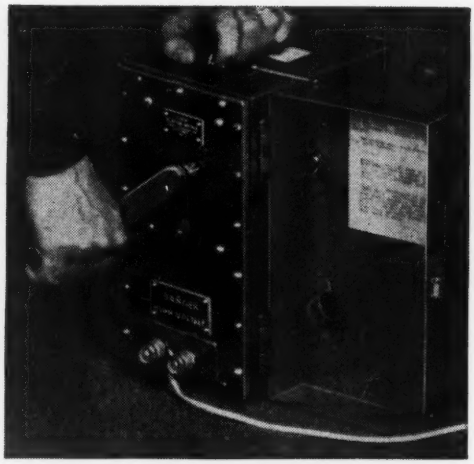

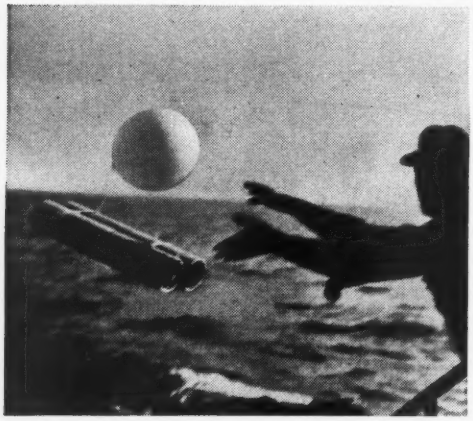

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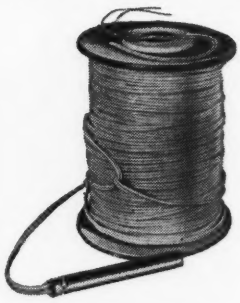

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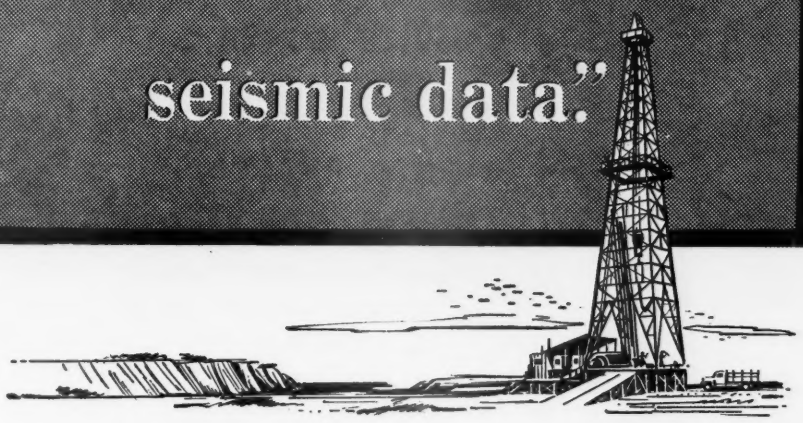

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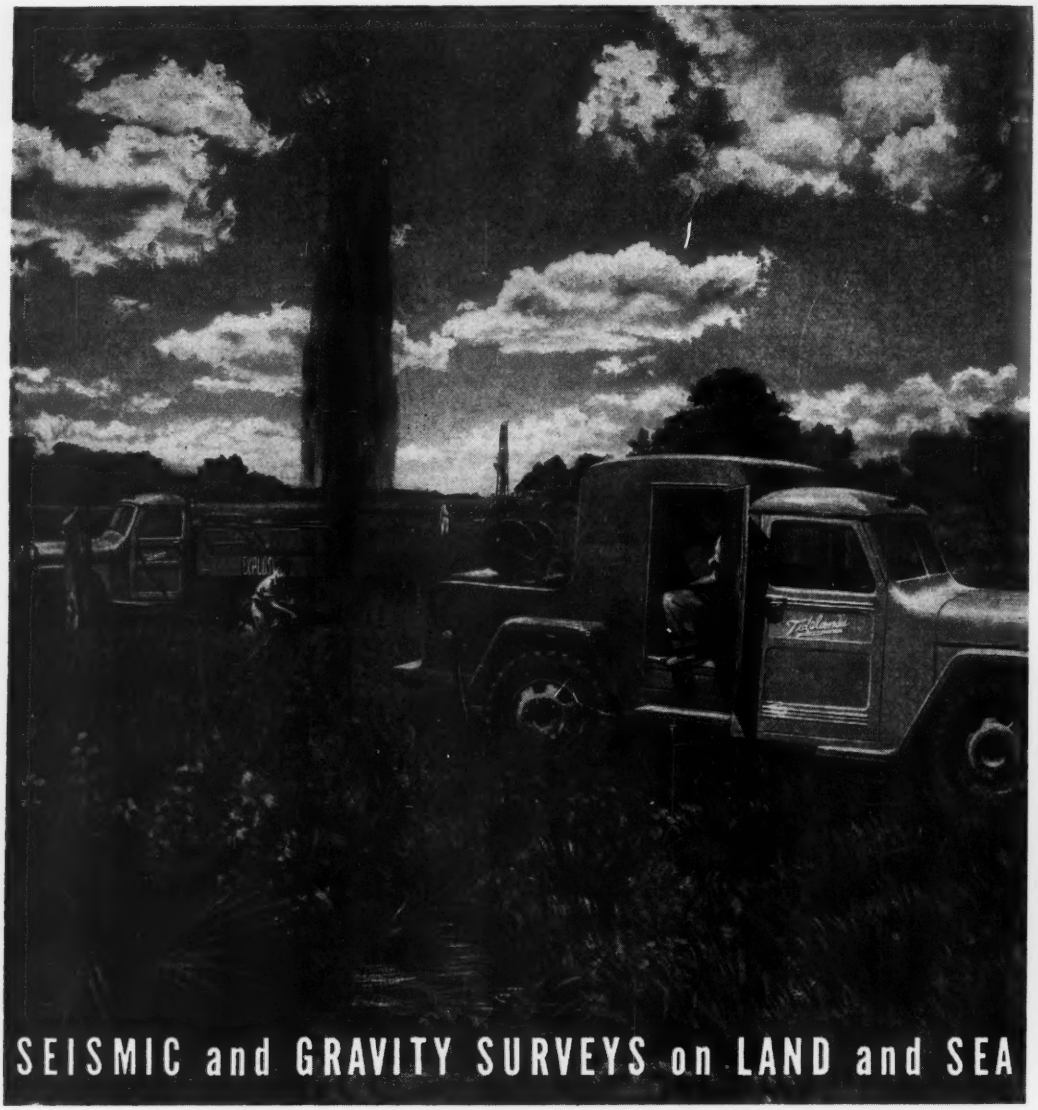

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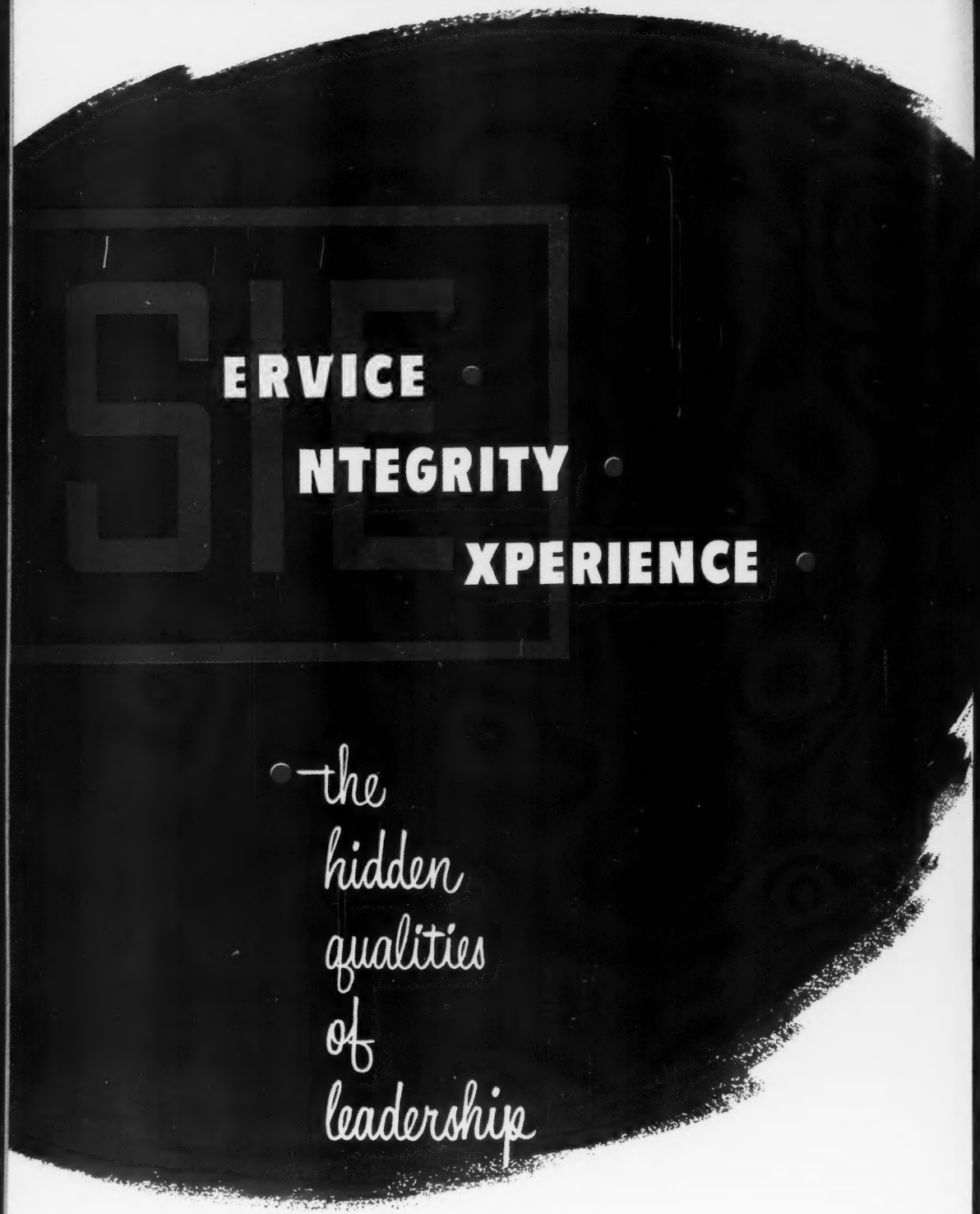

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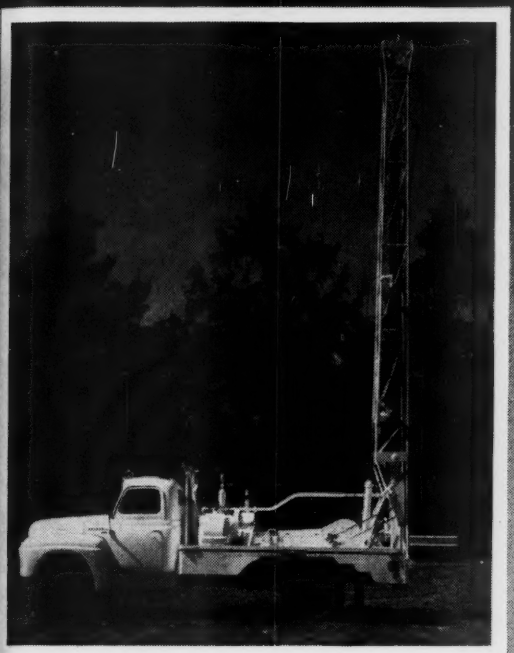

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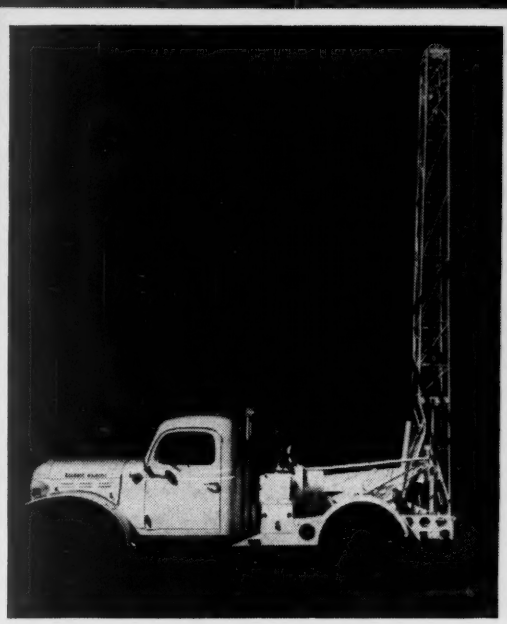

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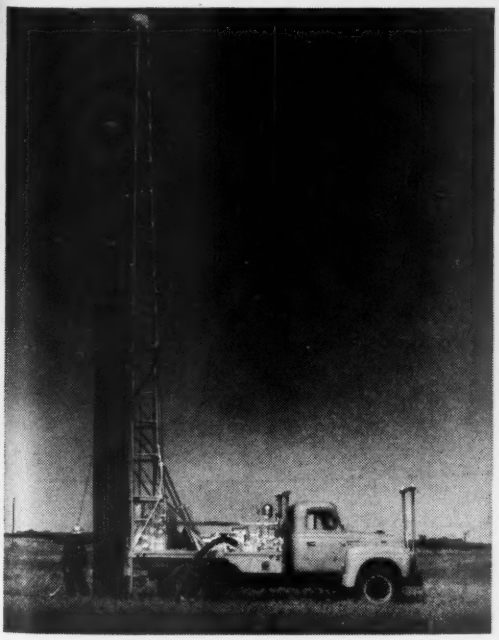

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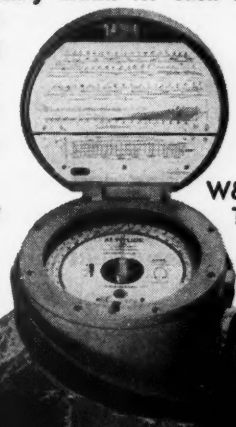

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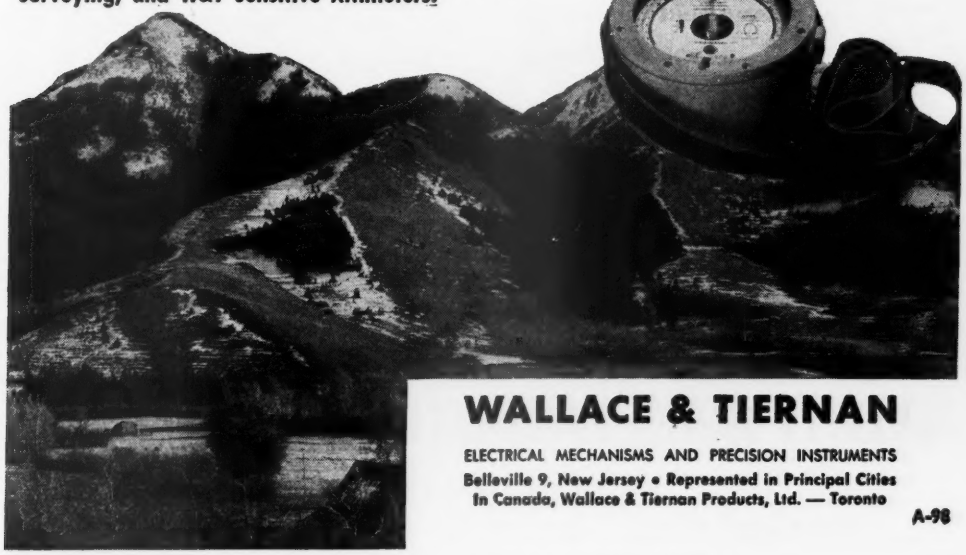

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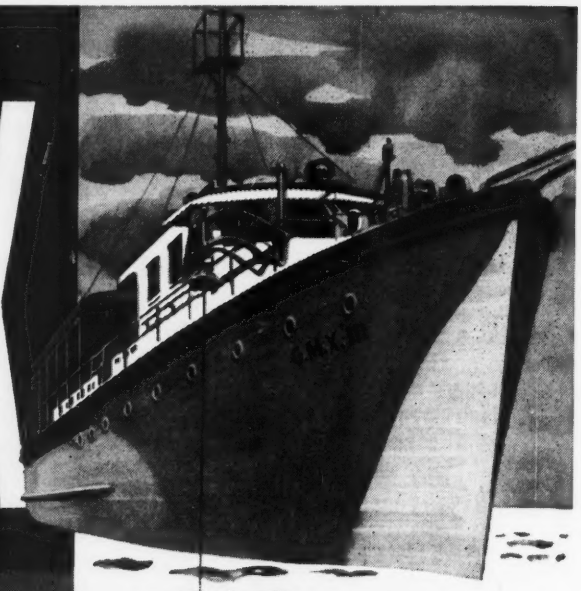

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GEOPHYSICS

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OUR EXPANDING HORIZONS*

ROY L. LAY†

ABSTRACT

Exploration assignments today are more challenging than ever before. The emphasis is on smaller structures and more accurate and deeper interpretations. Many of the more difficult areas, formerly not considered amenable to geophysical exploration, reveal a similarity of problems in widely separated geological and geographical provinces. Geologists and geophysicists are continually broadening their viewpoints because they realize more and more that few areas are unique.

Geophysics has made and is continuously making substantial contributions to basic geology. Exploration thinking is broadening steadily toward more definite evaluation of the many types of oil-bearing traps.

Explorationists are learning the principles of sound business risk and thereby expanding their horizons by becoming good businessmen as well as highly trained specialists. The opportunity to expand our horizons further was never more promising than at the present.

Today, our exploration assignments are more challenging than ever before. The emphasis is on smaller structures and more accurate and deeper interpretations, and we are working many of the more difficult areas which formerly were not considered amenable to geophysical exploration. Our record for the first 30 years of geophysics reflects a steady and continuous growth in our exploration thinking, in our technical skill, and in our business acumen. The experience gained in those past years will stand us in good stead in the years ahead, and I am confident that our exploration horizons will continue to expand in the future. I propose to discuss some evidence and reasoning which lead to that conclusion.

In the early days of geophysical exploration, many of the problems we encountered seemed to be new and different. Through experience and by observation of similar geophysical results and geological conditions in widely separated areas, we have since come to realize that actually very few areas or problems are unique.

Let us compare, for example, the Gulf Coast province with one of the large sedimentary basins of California. These regions have many similarities although they differ in that Gulf Coast structures generally are associated with salt uplift

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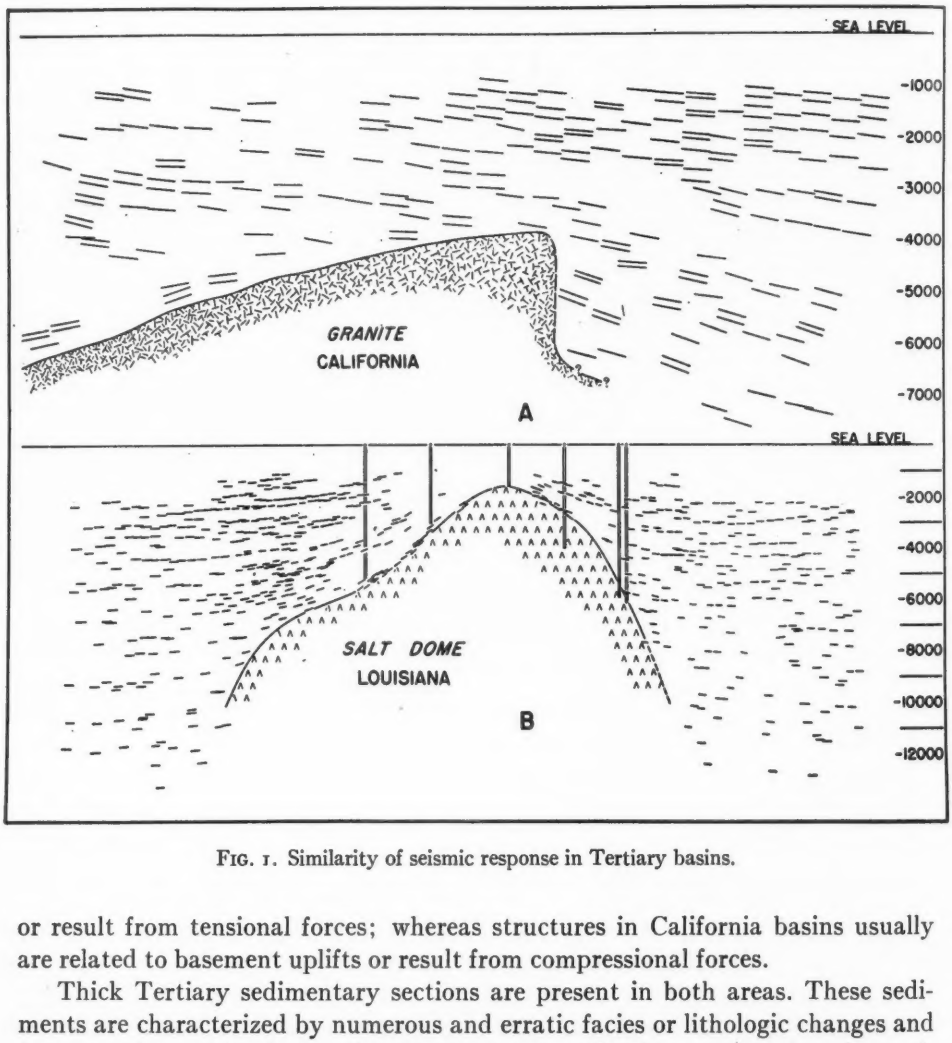

FIG. 1. Similarity of seismic response in Tertiary basins.

or result from tensional forces; whereas structures in California basins usually are related to basement uplifts or result from compressional forces.

Thick Tertiary sedimentary sections are present in both areas. These sediments are characterized by numerous and erratic facies or lithologic changes and few extensive marker beds, with the result that reflection response is quite variable. Although individual seismic records may be good, very few reflections are persistent and it is usually necessary to resort to phantom horizon interpretation. Figure 1 shows two typical seismic cross sections: "A," over a buried basement uplift in California, and "B," across a piercement-type salt dome in Louisiana. In both instances, the absence of reflections within the basement and salt masses is very noticeable, and is sufficiently definitive in the case of the salt dome to outline the flanks of the structure. Although both areas show good reflection response, the absence of extensive correlations is noticeable. It is readily apparent that the salt was intruded during or after deposition of the sediments, while the basement high was erosional and possibly faulted prior to the filling of this valley. The pro-

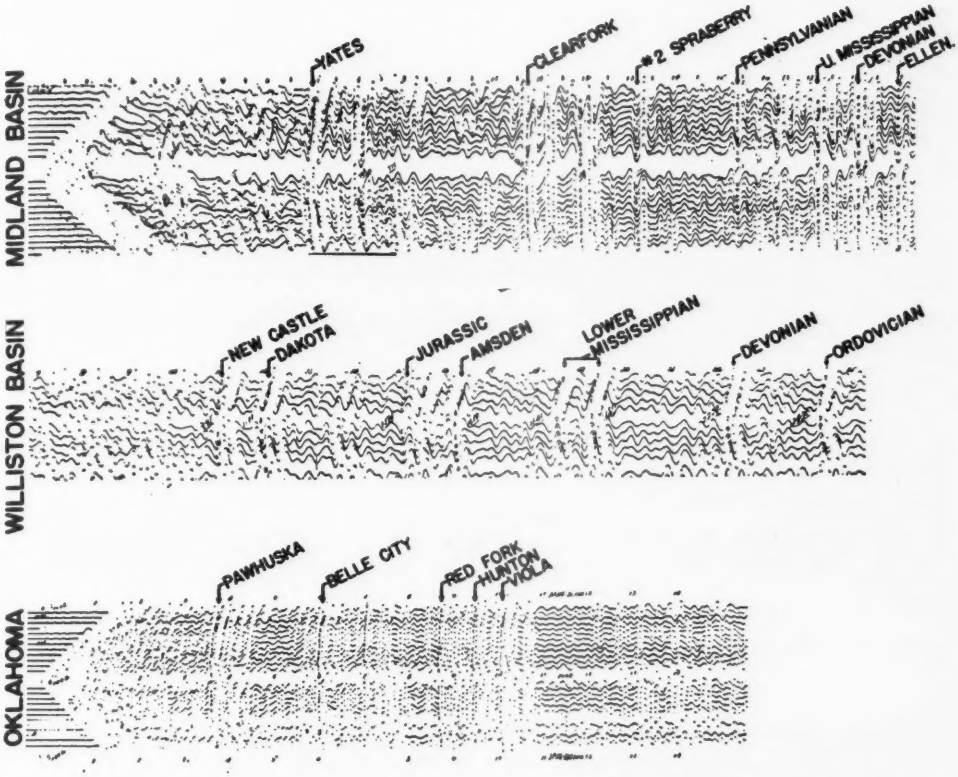

FIG. 2. Reflection records showing typical response in carbonate basins.

file of the salt mass as indicated by the reflection work is substantiated by well control, while the configuration of the basement high was obtained from refraction shooting.

Gravimetrically, the dense igneous rocks of the basement highs in California and the less-than-average density of the salt domes in the Gulf Coast provide measurable contrasts with the relatively minor density differences within the Tertiary sediments. Structural highs are, therefore, quite often associated with gravity maxima in California and with gravity minima in the Gulf Coast. In the examples illustrated by Figure 1, the salt dome has a minimum or negative gravity relief of about five milligals and the buried granite high a maximum or positive relief of approximately two milligals.

By contrast, in basins where carbonate rocks are present, persistent and characteristic reflections usually are obtained. Figure 2 shows some well-known key reflections in a few carbonate areas such as the Midland Basin, the Williston Basin, and in Oklahoma. The excellent correlation quality of such key reflections in a fourth carbonate rock area is illustrated in Figure 3, which shows the correlation of the Georgetown reflection in four counties in South and East Texas.

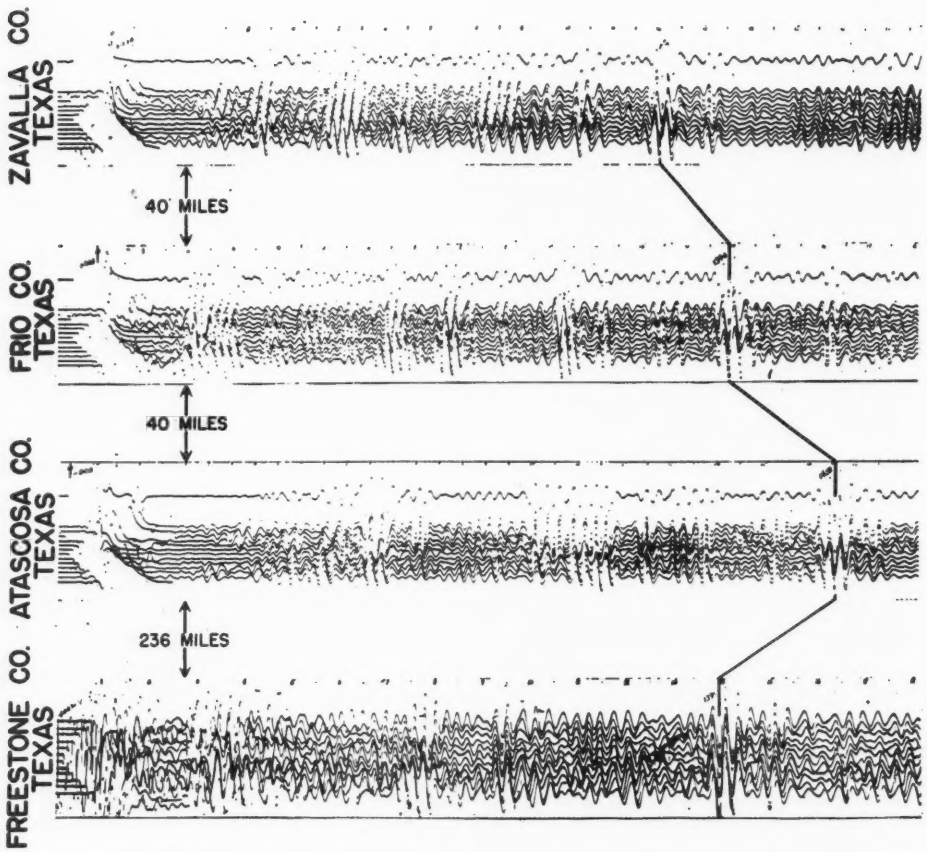

FIG. 3. Correlation quality of reflection from Georgetown limestone, Texas.

There is little question about the identification of this reflection over distances of from forty to three hundred miles in a general northeast-southwest direction and covering a depth range of 5,800 to 8,100 feet. Such extensive correlations are not uncommon in carbonate rock areas, and the structural configuration of new basin areas has, in many instances, been mapped by regional correlations of similar outstanding reflections.

Figure 4 shows typical seismic cross sections from structurally complex areas in California, Oklahoma, and in the Rocky Mountains. The geologic similarities are obvious and well-known. The geophysical approach is essentially the same in all three areas. Each of the three illustrated areas is characterized by steep, occasionally erratic dips, sharp folding, and evidence of abundant faulting. On the Rocky Mountain and California cross-sections unconformities are present and identifiable. Obviously, it is essential to analyze the data in three dimensions since many of the reflections may originate far from the plane of the cross section.

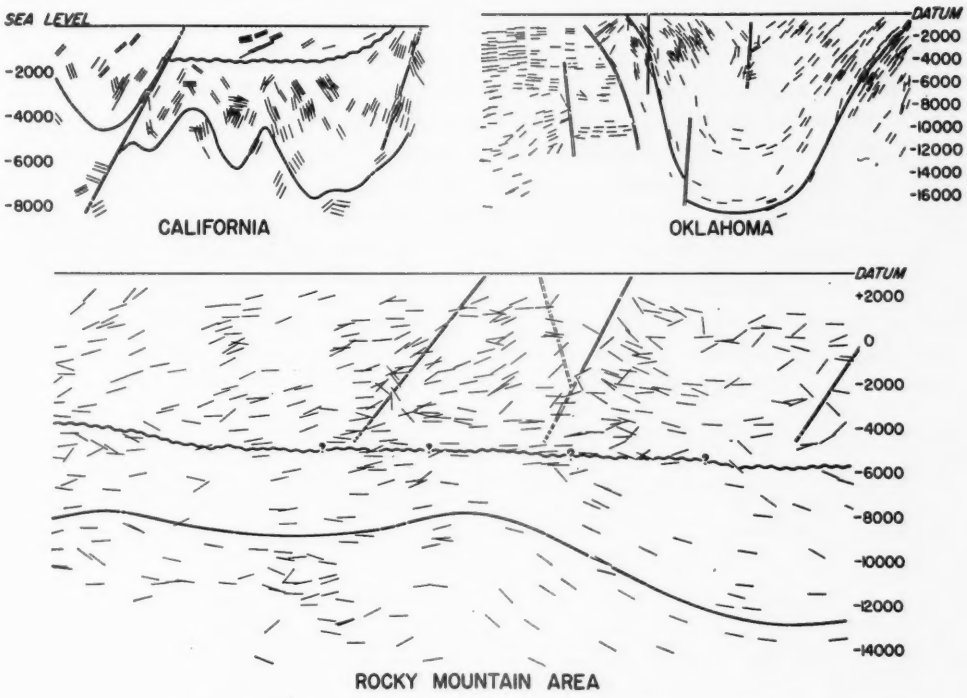

FIG. 4. Typical seismic cross sections in structurally complex areas.

In such areas the seismic interpreter walks a narrow ledge in trying to unravel the complex structure. He is confronted with a choice of an oversimplified, a very complicated, or some middle-of-the-road interpretation.

The recognition of the basic truism that few areas are unique, and the application of past experience to new exploration assignments has increased our overall effectiveness through the years. We still have problems and problem areas, however, which, although similar to other areas in many respects, require something more than a standard geophysical approach. Evidence of our growth as explorationists is our ability to utilize similarities to good advantage, and our versatility in modifying and improving our geophysical techniques to cope with the special problems.

It was inevitable that the study of geophysical results would lead to the question of geologic cause, and awaken interest among geophysicists in fundamental geologic problems. Geophysics gives measurements of the total thickness of sediments in deep basins; and it often changes or strengthens existing ideas regarding the extent and magnitude of unconformities, the presence of intrusives, and the position and age of faulting. As a result, geophysicists have made and are making substantial contributions to basic geological thinking, and to the solution of many specific geological problems.

Some geophysical investigations, such as those of Ewing and Gutenberg, have been conducted primarily for scientific purposes, but most of geophysics' contributions to geology have come as by-products of routine oil exploration. Although early torsion balance work in the San Joaquin and Santa Maria Valleys may not be credited with the discovery of any new oil fields, it did effect a better understanding of the structure buried beneath the flat valley floors. Later, refraction and reflection seismic results showed further the general configuration of the basement complex under the eastern part of the San Joaquin Valley. Quoting from Vaughan (1943):

"Reflection shooting has added considerably to knowledge of the general tectonic geology in many parts of California. Work in the Los Angeles Basin, for example, bears out the importance of block faulting in the development of the Basin."

Experience has shown this condition to exist in many other basins and geologic provinces.

Evidence for the existence of a Gulf Coast geosyncline was originally stratigraphic and gravimetric. Based on the results of offshore seismic information, the position of the axis has been shifted farther and farther seaward.

In the middle and late 1940's, geophysics made a substantial contribution to our understanding of the tectonics of the Central Basin Platform area of West Texas by pointing out the prevalence of pre-Permian faulting.

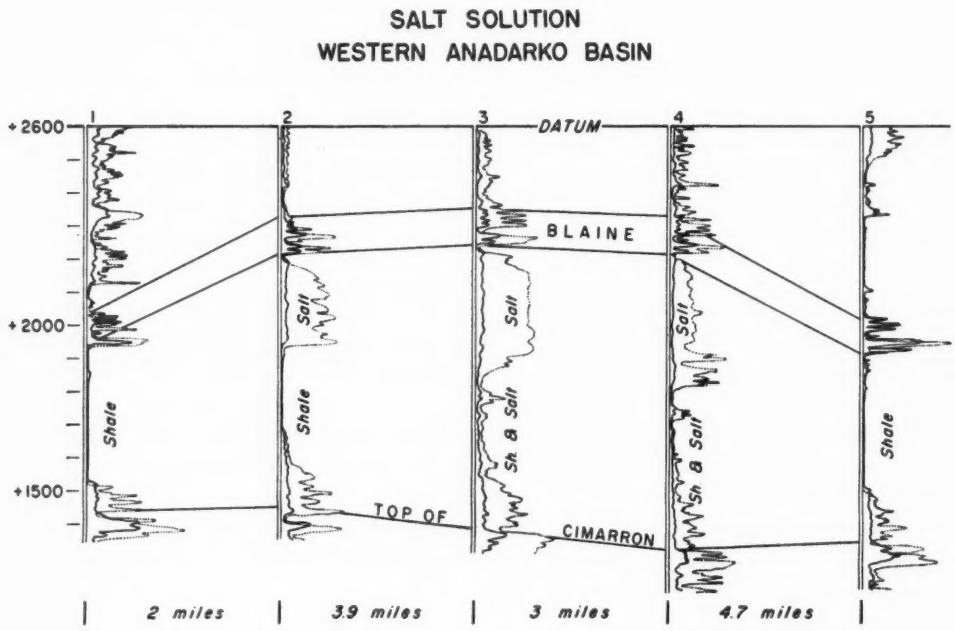

FIG. 5. Residual Blaine high due to salt solution—Anadarko Basin.

Geophysicists undoubtedly will continue to broaden their interest in these basic problems, the solution of which will ultimately lead to the discovery of new oil fields.

Industry's ingenuity in solving exploration problems has been demonstrated many times and in various ways. One notable example in the Western Anadarko Basin concerns the variable amounts of salt present within the Upper Permian. The salt-bearing formation was subjected to ground-water action subsequent to its deposition and there are considerable local variations in the amount of salt removed. This erratic condition is illustrated in Figure 5. The salt has been almost completely removed at core holes one and five, whereas considerable salt remains in core holes two, three, and four. The removal of salt at core holes one and five has resulted in a pronounced slumping of the Blaine. Thus a Blaine high is produced which is not reflected by the underlying Cimarron formation.

The variable and often abrupt changes in the amount of the high-velocity salt produced a difficult seismic problem which was first recognized as a result of abnormal and erratic dips. Consultations with the geologists directed attention to the shallow salt formation as the possible source of the difficulty. A core hole program was then initiated, and velocity surveys of these tests were run. Data from core tests on Blaine highs and lows resolved the problem, and interpretational methods were developed to remove the velocity distortion from the seismic data. Failure to correct for the variable salt effect would result in a very serious error to the extent of completely reversing the seismic dip. Widess (1952) has previously presented some other examples of this same salt solution problem.

If we are to continue to expand our exploration horizons, however, we cannot tarry to bask in the warm glow of past accomplishments. Proof that we are not resting on our laurels is clearly evidenced today by industry's probing search for more facts concerning many of the basic physical variables which are fundamental to geophysical interpretation. Cortes (1953), in his recent paper "Geophysical Progress," gives an excellent summary of the advancements in instrumentation and interpretation since geophysics was introduced into this country in 1921. He also describes briefly some of the research projects currently being conducted by industry such as: investigations of the physics of seismic wave propagation, analysis and identification of waves producing "noise" on seismic records, magnetic tape recording, application of electronic computing machines to record analysis, and density determination by means of borehole gravimeters and gamma-ray absorption analysis.

Our basic exploration thinking is also advancing and widening. Originally, geophysics sought only the major structures such as Wilmington and Paloma in California, Wasson of West Texas, Cumberland of Oklahoma, Salem of Illinois, and the salt domes of the Gulf Coast. Old reports in the files of many companies probably contain recommendations like this one: "Feature No. 7 is not considered sufficiently prospective to warrant the acquisition of acreage, as only one hundred feet of closure is shown." By now, industry is mapping and drilling struc-

tures with only 25 ft of closure, and even noses or terraces with possibly no evidence of closure. But in partial compensation, where there were only dozens of the giant structures, there are thousands of the smaller ones. This change in our objective has had to be accompanied by a change in our basic thinking. We can no longer afford to make maps on only outstanding reflections, such as those from the Viola of Oklahoma, the Lower Cretaceous of Alberta, or the Georgetown of northeastern Texas. Instead, we must often use reflections so weak and poor that they appear insignificant. In one prolific reef area, geophysicists have learned through experience that the only reef evidence obtained by the seismograph is from a weak, obscure reflection which usually shows radically different dip from that of immediately adjacent prominent reflections.

Several years ago, Paul Weaver (1951) urged that we should avoid averaging and generalizing in the construction of our structural maps, and that we give due regard to apparently erratic or spurious reflections which often may be of particular significance. He urged caution in the use of phantom horizons. In the early days of seismic exploration in Illinois, a party chief questioned the Devonian reflection, which split up and indicated an abnormal local thickening of the Devonian-Trenton interval. In this local area he resorted to a phantom horizon, because all geologists and geophysicists "knew" then that the Devonian-Trenton interval was constant. We have since learned better. We know now that this interval did, in fact, thicken, due to the presence of an intervening Niagaran reef, and that the peculiar Devonian reflection was correct and significant.

Our exploration thinking has broadened in other ways. In the late thirties a geophysicist pointed out that Pennsylvanian coral reefs in north-central Texas would cause false structure to be mapped on deeper beds because of velocity differences, and that dry holes might be drilled as a result. During the last several years, we have been busy searching for those very reefs which were once regarded as a hazard to seismic exploration.

We are only at the threshhold in applying geophysics to the search for stratigraphic traps, but undoubtedly progress is being made. Some of the advances may now be veiled in secrecy and only gradually become generally known. Others may be revealed quickly. One company advertised last year its success in mapping the shoestring sand pools of eastern Oklahoma and Kansas—long, sinuous pools, often only one location wide.

Similar changes in our exploration thinking are sure to occur in the future. We can be certain that these changes will not narrow our thinking, but will broaden it, and likewise will broaden our opportunities.

In the past few years, we have enjoyed outstanding success by extending our exploration activities to such relatively unexplored areas as the Williston Basin of the Rocky Mountain area, the Alberta Plains of Canada, the Cuyama Valley of California, and the deeper parts of the Midland Basin of West Texas. The vast offshore areas of the Gulf of Mexico and California are being revived. We realize, however, that there is a definite limit to the number of new basins, and that in the

foreseeable future, geophysical and geological exploration will have been extended to all of them. But we also know that none of the oil provinces has been so thoroughly explored that all its possibilities have been exhausted. In many of the deeper basins, we have done no more than scratch the surface with our geological and geophysical exploration, and the drill has penetrated only a small part of the total sedimentary section. Our geophysical efforts, particularly with the reflection seismograph, are constantly being directed toward obtaining deeper interpretations and much progress has been made. Herein lies one of the great opportunities to expand our horizons. The drill has thrown us a challenge by keeping pace with, and in some cases surpassing, the geophysicist in ability to penetrate to great depths. Just recently the Shell Oil Company completed the world's deepest commercial producer at a depth of 17,260–17,306 feet in the Weeks Island field on the Louisiana Gulf Coast. Ohio's deep Paloma field test in California was drilling below 21,300 feet at the time this paper was written.

Our success in some of the older, more heavily prospected areas has been below expectations in recent years. Both the number and size of drillable prospects discovered has been steadily decreasing. This decline has been the cause of great concern throughout the industry. We are striving to meet this challenge by improving our field techniques and instruments, and by sharpening our interpretations in order to obtain a more accurate definition of faults and stratigraphic traps. No doubt, greater refinements will be necessary to insure effective exploration programs in these areas in the future.

We have learned from past experience that basins, which today may be considered non-prospective due to the supposed absence of sediments and structures favorable for oil accumulation or because of unfavorable economic factors, may suddenly become very prospective as the result of some new development. An excellent example of this is the discovery of production from Pennsylvanian reefs in Scurry County, which ignited a tremendous reef play. The Williston Basin lay dormant for many years until Amerada's discovery on the Nesson Anticline showed the potentialities of that large area.

These possibilities present us, as explorationists, with unlimited opportunities to demonstrate our ingenuity by imaginative and aggressive thinking directed toward further expanding our horizons.

The review of old seismic and gravity data has been carried on at an accelerated pace in recent years. Gratifying dividends in the form of new prospects and leads to new prospects have resulted. Considerable savings in lease rentals have been made on acreage no longer considered prospective.

We probably all have maps in our files that are based on data which, in the light of present day requirements, are inadequate. A contoured interpretation, whether it be geophysical or geological, tends to give us a feeling of security. We are content in the belief that our coverage is adequate, and our interpretation reasonably accurate. Then, all too often, our complacency is shattered by a competitor's discovery in our syncline or zone of remarkably uniform regional dip.

It is my firm belief that a review staff can make substantial contributions in this regard by pointing out such potential danger areas.

It is true that we all learn from past mistakes, yet the geophysicist engaged in the interpretation of current data rarely has the opportunity or time to find out how his previously completed interpretations check with new well control. The review staff, on the other hand, spends considerable time investigating disagreements between geophysical and geological data. It is, therefore, in a position to observe the reasons for past mistakes and suggest improvements in field techniques and interpretive methods to correct them. More and more of this effective and economical type of exploration will be done in the years ahead.

This technical age tends to produce specialists whose academic training and practical experience is frequently narrow in the sense that it is restricted to a particular field or even a part of one field. Unfortunately, explorationists have long been so classified, and only through their individual efforts can they escape this narrowness. Industry is now recognizing the need for and the advantages of broadening the training and experience of its specialists; consequently, many companies now have well organized training programs in which geophysicists and geologists each gain an understanding and working knowledge of the other's problems. The geologist is assigned to a geophysical party for a prescribed course of training in field techniques and in calculation and interpretation of the data. Similarly, the geophysicist is assigned to a geological office for training in the many phases of geologic mapping, stratigraphic studies, and the interpretation and use of electric logs. He becomes more familiar with the details of the geologic section and learns how facies changes and varying geologic conditions may affect his geophysical results. Emphasis is placed on the proper coordination of geological and geophysical data and he is acquainted with the various types of productive structural and stratigraphic traps in the area in which he is working. The geologist becomes more familiar with the advantages and limitations of the geophysical methods, i.e., he knows the high resolving power of the reflection seismograph, but also learns that in some basins gravity meter and magnetic surveys are effective to delineate local subsurface effects. By association with geophysicists he learns something about the adaptability of the various geophysical tools to fit the problem at hand. Thus, in his recommendations for geophysical work, the geologist is better able to give a considered opinion as to the type of survey required. This can result in an economy of time as well as expense unless he overestimates the capabilities of the geophysicist, as in the classic example of the geologist who, some years ago, recommended seismic work in an Appalachian Basin area because "the terrain was too rugged to permit entry of the surface geologist on horseback."

The training courses are not intended to make an expert geophysicist out of a geologist, or vice versa; but they have been very successful in developing a sympathetic and mutual understanding of each other's problems. Perhaps even more important is that, through these courses, the geologists and geophysicists get to know each other personally, furthering their cooperation. Those of you

who have participated in or supervised such programs will undoubtedly agree that much mutual benefit results, and that those so trained have greatly broadened their viewpoints.

The last but by no means least important reason that our horizons are expanding is the fact that as scientists searching for new oil fields, we are becoming good businessmen. Since the close of World War II, the number of seismic parties in the world has increased from about 400 to over 1,000; the membership of SEG has increased from 1,300 to 4,000; and of AAPG, from 4,500 to 10,000. With this tremendous growth in exploration work, geophysicists and geologists have been called upon to assume more and more responsibility. This is a natural development in view of the very large expenditures involved in modern exploration, and it becomes particularly important in these times of closely controlled budgets. The days are gone when a party chief need not concern himself with the operating cost of his party. The party chief today must keep a close check on shothole drilling, explosives, extra labor, and all other controllable items of expense. The geologist, similarly, must watch his recommendations, particularly in areas of high lease costs, keeping in mind the reliability of his interpretation. This matter of being a good businessman starts in the field, but whether it be on a geophysical field party or in a district geological office, the geophysicist and the geologist each has ample opportunity to develop and demonstrate his business ability. However, these commercial aspects should only supplement his scientific thinking. He must continue to be optimistic in evaluating his data, and at the same time learn the principles underlying sound business risk.

The success of geologists and geophysicists in expanding their horizons, by broadening their interests and technical abilities, and by becoming good businessmen, is evidenced by the fact that their talents are being recognized more and more by the executives of industry and they are being promoted into high-level positions of management in many companies.

In conclusion, I want to say that we explorationists are fortunate to be engaged in such a fascinating and satisfying part of the petroleum industry, and I believe the opportunity to expand our horizons even further through conscientious resourcefulness and hard work was never more promising. The future is bright and I urge you to make the most of this splendid opportunity.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance of my associates, Messrs. W. H. Gibson, J. M. Kendall, D. H. Scott and Ted Pilcher, in the preparation of this paper and illustrations.

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TWO-DIMENSIONAL MODEL SEISMOLOGY*

JACK OLIVER,† FRANK PRESS,† AND MAURICE EWING†

ABSTRACT

The solutions of many problems in seismology may be obtained by means of ultrasonic pulses propagating in small scale models. Thin sheets, serving as two dimensional models, are particularly advantageous because of their low cost, availability, ease of fabrication into various configurations, lower energy requirements, and appropriate dilatational-to-shear-velocity ratios. Four examples are presented: flexural waves in a sheet, Rayleigh waves in a low velocity layer overlying a semi-infinite high velocity layer, Rayleigh waves in a high velocity layer overlying a semi-infinite low velocity layer, and body and surface waves in a disk.

INTRODUCTION

In recent years investigators in both the commercial and academic fields have attacked the problems of elastic wave propagation by studying waves of ultrasonic frequencies traveling through small scale three-dimensional models, and a few papers have been published on the subject (Kaufman and Roever, 1951; Northwood and Anderson, 1953; Terada and Tsuboi, 1927). Although promising results were obtained, widespread application of the method to significant problems has been slow, chiefly because of the difficulties in procuring suitable model materials and in the fabrication of desirable configurations. This paper describes the use of two-dimensional models, which virtually eliminates these and other difficulties without detracting from the usefulness of the method in a great majority of cases.

The models take the form of thin sheets and the propagation takes place along directions lying in the plane of the sheet. In practice these sheets are generally 1/16 inch thick, and only wavelengths long compared to this thickness are employed.

THEORY

We wish to determine the velocities of propagation of dilatational and shear waves in a thin plate and of Rayleigh waves on the edge of a thin plate. We restrict ourselves to waves in which the particle motion is symmetrical about the median plane of the plate, thus excluding any type of wave motion which involves bending of the thin plate.

Love's concept of a "generalized plane stress" (Love, 1944) is applicable and most convenient. The x and y directions are taken in the plane of the plate, the z direction perpendicular to it. X_y is the stress in the x direction on the face normal to the y axis, etc. Love's concept supposes the stress Z_z to vanish throughout the plate and the tangential stress Z_x and Y_z to vanish at $z = \pm h/2$ only,

* Manuscript received by the Editor December 7, 1953.

† Lamont Geological Observatory, Columbia University, Palisades, N. Y.

where h is the plate thickness. For a thin plate, Love takes average values of the components of displacement, strain and stress, e.g.

$$\bar{u} = \frac{1}{h}\int_{-h/2}^{h/2} u\,dz.$$

u and v are the displacements in the x and y directions respectively.

In the following we use only average values for these quantities and the bar is omitted.

The equations of motion are

$$\frac{\partial X_x}{\partial x} + \frac{\partial X_y}{\partial y} = \rho\frac{\partial^2 u}{\partial t^2}, \qquad \frac{\partial Y_x}{\partial x} + \frac{\partial Y_y}{\partial y} = \rho\frac{\partial^2 v}{\partial t^2} \tag{1}$$

where ρ is the density.

The average stress components are given by Love as

$$X_x = \frac{2\lambda\mu}{\lambda + 2\mu}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + 2\mu\frac{\partial u}{\partial x} \tag{2a}$$

$$Y_y = \frac{2\lambda\mu}{\lambda + 2\mu}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + 2\mu\frac{\partial v}{\partial y} \tag{2b}$$

$$X_y = \mu\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right). \tag{2c}$$

Substituting (2) into (1),

$$\rho\frac{\partial^2 u}{\partial t^2} = \left(\frac{2\mu\lambda}{\lambda + 2\mu} + \mu\right)\frac{\partial \tau}{\partial x} + \mu D^2 u \tag{3}$$

and similarly in v, where

$$\tau = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \quad \text{and} \quad D^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}.$$

Differentiate equation (3) with respect to x and the similar equation in v with respect to y and add the results to obtain

$$\rho\frac{\partial^2 \tau}{\partial t^2} = \frac{4\mu(\lambda + \mu)}{\lambda + 2\mu} D^2\tau. \tag{4}$$

Equation (4) checks the velocity given by Lamb for dilatational waves in a thin plate, i.e.

$$V_p = \left[\frac{4\mu(\lambda + \mu)}{\rho(\lambda + 2\mu)}\right]^{1/2}. \tag{5}$$

Take the curl (two dimensional) of equation (3) to obtain

$$\rho \frac{\partial^2}{\partial t^2}\left(\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x}\right) = \mu D^2\left(\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x}\right). \tag{6}$$

Thus the shear wave velocity is the same as in an infinite solid, i.e.

$$\beta = \left(\frac{\mu}{\rho}\right)^{1/2}.$$

We now consider a thin plate which occupies the xy plane from $y=0$ to $y=+\infty$. Let

$$u = \frac{\partial \phi}{\partial x} + \frac{\partial \psi}{\partial y}, \qquad v = \frac{\partial \phi}{\partial y} - \frac{\partial \psi}{\partial x}; \tag{7}$$

then

$$D^2\phi = \tau, \qquad D^2\psi = \frac{\partial u}{\partial y} - \frac{\partial v}{\partial x}$$

where ϕ and ψ satisfy

$$\frac{\partial^2 \phi}{\partial t^2} = V_p{}^2 D^2\phi, \qquad \frac{\partial^2 \psi}{\partial t^2} = \beta^2 D^2\psi. \tag{8}$$

Choose plane wave solutions of the form

$$\begin{aligned} \phi &= Ae^{ik(-ry+x-ct)} \\ \psi &= Be^{ik(-sy+x-ct)} \end{aligned} \tag{9a}$$

where

$$r = \left(\frac{c^2}{V_p{}^2} - 1\right)^{1/2}, \qquad s = \left(\frac{c^2}{\beta^2} - 1\right)^{1/2}. \tag{9b}$$

c is the velocity of propagation of constant phase in the x direction and k the wave number. Thus the wavelength in the x direction, l, is given by $l=2\pi/k$ and the period T by $T=2\pi/kc$.

At the free edge $y=0$,

$$X_y = Y_y = 0. \tag{10}$$

Using equation (2), (7), (9), and (10) we get

$$[V_p{}^2(1 + r^2) - 2\beta^2]A + 2\beta^2 sB = 0 \tag{11}$$

$$2rA + (1 - s^2)B = 0. \tag{12}$$

Eliminating A and B from (11) and (12) and using (9b)

$$\left(2-\frac{c^2}{\beta^2}\right)^2=4\left(1-\frac{c^2}{V_p{}^2}\right)^{1/2}\left(1-\frac{c^2}{\beta^2}\right)^{1/2}. \tag{13}$$

This is identical with the equation for Rayleigh waves on the surface of a semi-infinite solid (Bullen, 1947) with the exception that the plate dilatational velocity replaces the infinite solid dilatational velocity. It is clear that no difficulties will arise in more complicated cases. Thus most of the problems on propagation of plane waves in a stratified earth may be related to the two dimensional models simply by replacing α by V_p.

EQUIPMENT AND TECHNIQUES

The principal features of the apparatus and procedure are described here briefly. The transmitting and receiving equipment is adapted from similar equipment in use in several laboratories, but the use of thin plates for construction of the models is apparently novel.

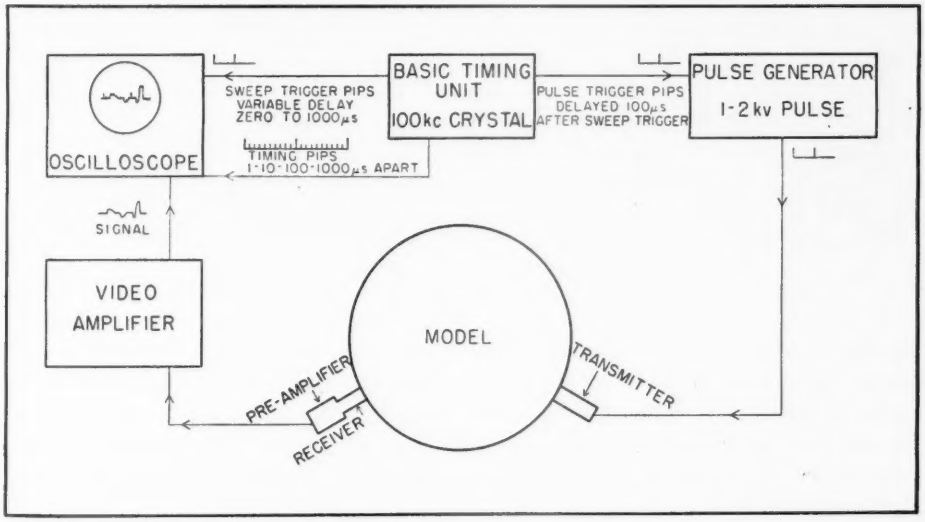

FIG. 1. Block diagram of apparatus.

A block diagram of the equipment is shown in Figure 1. Electrical pulses of approximately 15 microsecond duration are applied to the transmitter, a small piezoelectric element in contact with the model. This transducer delivers an acoustical pulse, shown as traced from the seismogram in Figure 2, to the model. The resulting acoustical energy arriving at various points on the model is detected by a similar transducer, amplified, and then displayed on the cathode ray oscilloscope. The pulse repetition rate is adjustable from 2 to 100 pulses per second. The oscilloscope sweep is triggered at a fixed time interval ahead of the pulse so that a standing wave pattern, including the time break, is observed. The basic

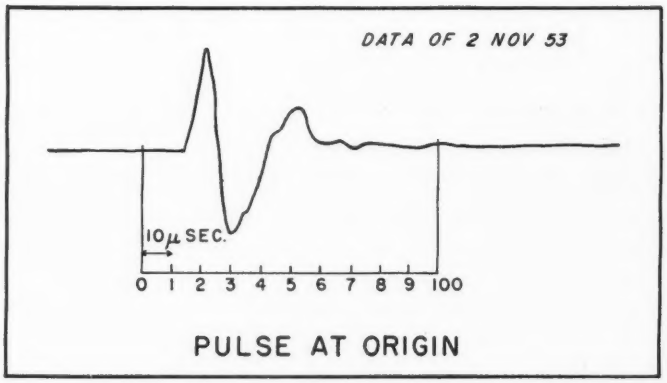

FIG. 2. Pulse at origin.

timing unit which initiates the trigger pulses for both the oscilloscope and the pulse also supplies timing markers at convenient intervals. The resulting pattern on the oscilloscope is then photographed by a Polaroid Land camera and the miniature seismogram is obtained immediately.

The transmitting transducer is a barium titanate cylinder 1/10 inch thick and $\frac{1}{4}$ inch in diameter. To prevent internal reflections in the source mount, the transducer is backed by a long aluminum rod of the same diameter. The part of the energy that enters the backing and then reflects from the end of the rod back toward the source is too late and too greatly attenuated to confuse the seismogram. Difficulties due to free oscillations or "ringing" of the source are avoided by utilizing a frequency range that is below the ringing frequency of the transducer. The receiving transducer is also of barium titanate 1/25 inch thick and 3/32 inch in diameter and is mounted in a similar but less elaborate manner. The smaller thickness further improves the reduction of ringing.

The electronic equipment is currently being improved and will be thoroughly described in a later report. The present unit delivers a pulse of about 1,000–2,000 volts to the source crystal. The voltage amplification of the receiving unit is less than 100,000.

The two-dimensional models are usually built in the form of disks. These are particularly advantageous for the study of surface waves on the edge of the disk since there are no reflections of the surface waves and since a very long path may be obtained by using the multiple trips around a relatively small disk. The curvature of the disk may be made small compared to a wavelength so that the usual surface wave equations for flat-lying strata will be applicable with the slight modification of the dilatational wave velocity, or it may be made larger for studying the effect of sphericity of the earth upon long period surface waves. The body phases of earthquake seismology may be studied in the usual manner very conveniently. Any degree of complexity in the layering may be obtained by means of concentric rings of various materials glued together in the desired rela-

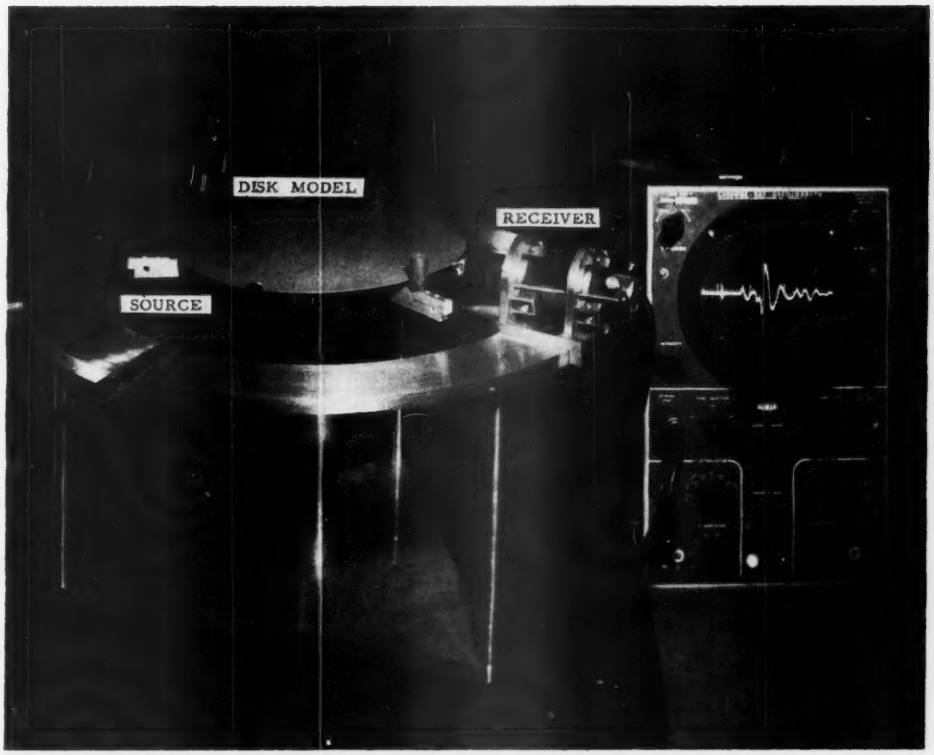

FIG. 3. Model, transducers, and oscilloscope.

tion. The diameters of the disks used in this study are about 20 inches. The thickness is at present standardized at 1/16 inch. This is small compared to all the wavelengths involved so that there is no dispersion due to finite disk thickness. For some types of problems shapes other than the circular might be desirable; e.g., refraction and reflection problems of seismic prospecting may be studied by constructing a cross section of the configuration in question. Table 1 lists the materials that have been sampled to date with the compressional, shear and Rayleigh velocities.

The disks are held in position by three rubber-covered supports which touch them at three points on the periphery (Figure 3). Experiments show that for a disk of this thickness the supports do not affect the surface wave propagation appreciably. The disk is mounted concentric with a graduated ring on which the receiver travels, allowing accurate measurement of all arc distances. The transmitting transducer is set at an arbitrary zero which may be determined accurately by running profiles from the transducer in both directions. A plot of the dilatational wave travel times vs. distance immediately gives the zero of the transmitted pulse in both time and distance.

COMPARISON OF TWO- AND THREE-DIMENSIONAL MODELS

Two-dimensional models (2-D) have the following advantages over three-dimensional (3-D) models.

1. The materials are far less expensive. 3-D models are usually constructed of some material which can be poured, e.g., wax, concrete, tars, or various chemical setting cements, or of some material which can be purchased in large slabs, e.g., limestone, marble, etc. All of these are expensive and become increasingly difficult to handle when layered media are desired. It is particularly difficult to pour materials in large blocks and maintain homogeneity throughout. The 2-D models, on the other hand, may be constructed of any material which can be bought in 1/16 inch sheets. This includes most metals and alloys and many types of plastics, fibers, etc. They are not prohibitively expensive and are generally far more homogeneous than poured materials.

2. The fabrication is greatly simplified. Layered configurations may be built up from concentric rings, easily cut to accurate specifications on a large lathe. Almost any sort of hard glue may be used as a binding agent.

3. Storage is simplified, a drawer of a map case may be used for storage of a large number of 2-D models. 3-D models frequently require about 50 sq ft of floor space for each model.

4. The energy requirements are greatly diminished in the 2-D model. For body waves the intensity varies as $1/R$, as opposed to $1/R^2$ in the 3-D case. Surface waves undergo no geometrical attenuation, instead of the $1/R$ variation in the 3-D case. This is a tremendous advantage as it allows the use of pulses of 1,000 volts or less as opposed to 5,000–10,000 volts in the 3-D case. Similarly lower gains may be used in the amplifying system, which permits use of a simple receiving circuit.

5. Most materials commercially available do not make good models of rock because Poisson's ratio is too large, usually about 0.33 as opposed to about 0.25 for rocks. In the 2-D model the dilatational wave velocity is altered (see theory) so that a pseudo-Poisson's ratio (the same relation of the dilatational and shear velocities as for Poisson's ratio) now falls in the range appropriate to rocks (see Table 1).

6. Multiple trips around the disk by the surface waves may be used to give large path distances. The present paper includes waves that have made $2\frac{1}{2}$ trips (about 13 feet) but waves have been observed that have made $7\frac{1}{2}$ complete circuits (about 40 feet). Although a similar scheme might be followed three-dimensionally by using a sphere, the construction of spheres, particularly with concentric layers, is very difficult.

The multiple paths also provide a means of measuring attenuation that is free of instrument calibration and differences in coupling of the model to the transducer. This approach is identical to that used in the measurement of the absorption coefficient of the mantle by means of long Rayleigh waves (Ewing and Press, in press).

TABLE I

MEASURED ELASTIC WAVE VELOCITIES AND DENSITIES

Material	Designation	Sample	Plate Dilatation Velocity V_p in ft/sec	Shear Velocity, β in ft/sec	Rayleigh Velocity, V_r in ft/sec	Density ρ in gm/cc	Pseudo-Poisson's Ratio: $\frac{\frac{1}{2}-(\beta/V_p)^2}{1-(\beta/V_p)^2}$	Remarks
Aluminum Alloy	24S-T4	Disk $\frac{1}{16}''\times 10.56''$	18,300	10,400	9,800	2.77	.26	
Plexiglass	Colorless, Transparent	Disk $\frac{1}{16}''\times 10.75''$	7,750	4,500	4,200	1.22	.25	
Panelyte	Grade 550	Disk $\frac{1}{16}''\times 19.522''$	10,650	6,000	5,600	1.44	.27	Anisotropic* 2%
Copper	Cold rolled	$\frac{1}{16}''\times 10.75''$	13,000	7,500	6,900	9.03	.25	
Steel	Cold rolled	$\frac{1}{16}''\times 10.75''$	17,850	10,650	9,700	7.78	.22	
Steel	Hot rolled	$\frac{1}{16}''\times 10.75''$	17,600	10,300	9,700	7.80	.24	
Brass	Half hard	$\frac{1}{16}''\times 10.75''$	12,500	7,000	6,500	8.34	.28	
Zinc		$.052''\times 10.75''$	13,100	7,700	7,300	7.07	.24	
Vinyl Plastic	Phonograph record	$\frac{1}{16}''\times 11.875''$	6,420	3,870	3,540	1.47	.21	
Fish paper	Franklin Fibre Lamitex	$\frac{1}{16}''\times 10.875''$	8,970	5,490	5,110	1.14	.22	Anisotropic* 22%
Fibre	Franklin Hard Vulcanized	$\frac{1}{16}''\times 10.875''$	8,650	5,270	4,900	1.06	.21	Anisotropic* 15%
Formica	Linen Laminate	$\frac{1}{16}''\times 10.75''$	8,450	5,050	4,700	1.30	.24	Anisotropic* 7%

* For anisotropic materials slowest velocities are tabulated. These are generally perpendicular to the grain. For Panelyte the tabulated velocity is an average.

At present 3-D models are necessary only when one or more layers of a stratified configuration is a liquid or when it is desirable to model three-dimensional effects such as reflections not in the vertical plane of the shot and detector, which might be encountered in seismic prospecting.

EXAMPLES

Flexural Waves

The experimental model for studying the propagation of flexural waves in a plate, as worked out by Lamb (1917), was a ring cut from 24 ST Aluminum sheet, 1/16 inch thick. The outside diameter $2R_2$ of the ring was 19.112 inches and the inside diameter $2R_1$, $\frac{1}{2}$ inch less. Radial motions of the ring were investigated as the 2-D analog of ordinary flexural waves. Figure 4 is a tracing of the oscillogram obtained with the receiver at the antipodes of the source. At this point there is constructive interference between the waves arriving from opposite directions. The first arrival following the time break corresponds to a dilatational wave through the ring. The first dispersive train of flexural waves corresponds to R_1 and R_2, the second to R_3 and R_4, etc., where the R's with subscripts are used in the same sense as in earthquake seismology. The values obtained from the experimental data are plotted as the small circles of Figure 5.

The theoretical equations for wave motion in an elastic plate in a vacuum were presented by Lamb (1917). The dispersion of flexural waves is determined by his period equation for asymmetrical motion. In our notation this equation takes the form

$$\frac{\tanh \frac{kh}{2}\left(1-\frac{c^2}{\beta^2}\right)^{1/2}}{\tanh \frac{kh}{2}\left(1-\frac{c^2}{\alpha^2}\right)^{1/2}} = \frac{\left(2-\frac{c^2}{\beta^2}\right)^2}{4\left(1-\frac{c^2}{\alpha^2}\right)^{1/2}\left(1-\frac{c^2}{\beta^2}\right)^{1/2}} \tag{14}$$

where h is the layer thickness.

To adapt this to our 2-D models we need only replace α by V_p and h by $R_2-R_1\equiv H$. Group velocity is obtained from the well known formula

$$U = c + \kappa H \frac{\partial c}{\partial(kH)} \cdot \tag{15}$$

A family of theoretical curves of group velocity vs. period computed with the constants for 24 ST Aluminum alloy is shown in Figure 5. Thickness is the parameter and very close agreement with the observed points is evident. Thus we have a good check on both the theory and the experimental method.

Slight complications have arisen due to the shape of the source pulse, in particular the later origin times of the longer periods. This difficulty may be completely circumvented by measuring arrival times of each period on successive

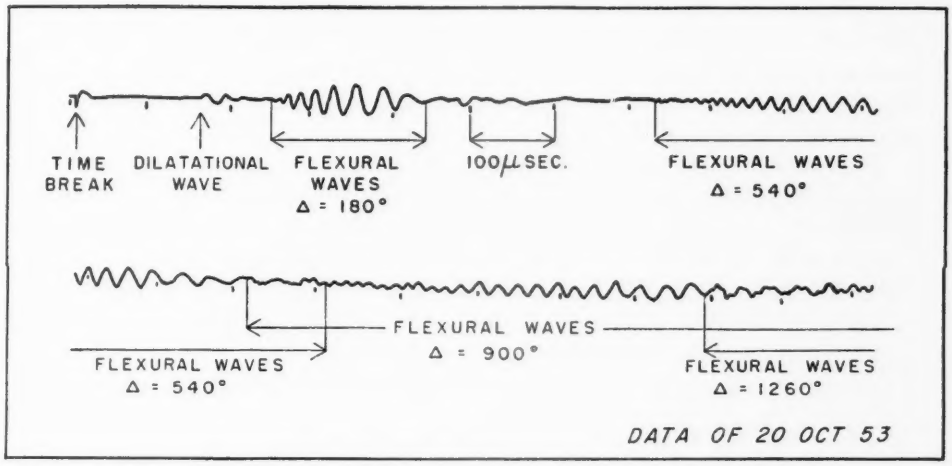
TIME BREAK
DILATATIONAL WAVE
FLEXURAL WAVES Δ = 180°
100μ SEC.
FLEXURAL WAVES Δ = 540°
FLEXURAL WAVES Δ = 540°
FLEXURAL WAVES Δ = 900°
FLEXURAL WAVES Δ = 1260°
DATA OF 20 OCT 53

FIG. 4. Seismogram—flexural waves.

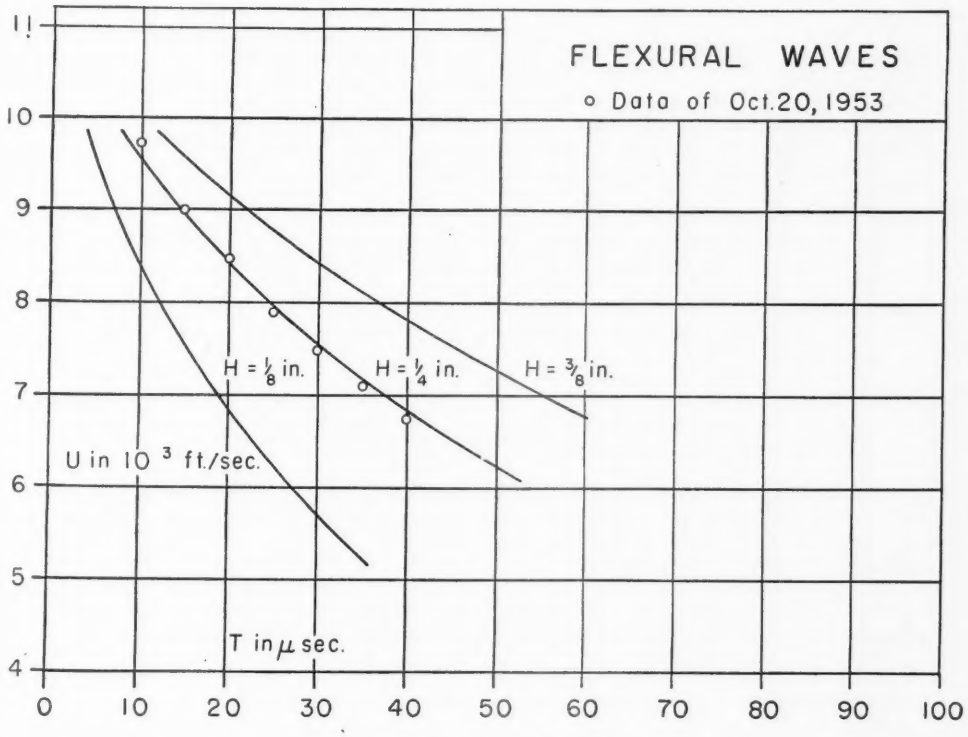

FIG. 5. Flexural wave dispersion.

trips around the ring and calculating the group velocity over the interval. The points of Figure 5 were obtained by this method. If the initial rise of the source is used as a time break, a maximum error of 2% in the velocity might result. This effect is interesting and will be the subject of future study but it does not affect the present results.

Rayleigh Waves—Low Velocity over High Velocity

The most common configuration in nature which produces dispersion in Rayleigh waves is comprised of a low velocity layer of thickness h over a high velocity semi-infinite layer. Lee (1932) has presented the theoretical equations for this case. His period equation is

$$\xi\eta' = \xi'\eta \tag{16}$$

where

$$\xi = \left(2 - \frac{c^2}{\beta^2}\right)\left[\left(\frac{c^2}{\beta'^2}\,\frac{\mu'}{\mu} - \phi\right)\cos kh\eta_1 + \frac{\eta_1'}{\eta_1}\left(\frac{c^2}{\beta^2} + \phi\right)\sin kh\eta_1\right]$$

$$+ 2\eta_2\left[\eta_1'\phi \sin kh\eta_2 - \frac{1}{\eta_2}\left(\frac{c^2}{\beta'^2}\,\frac{\mu'}{\mu} - \phi - \frac{c^2}{\beta^2}\right)\cos kh\eta_2\right]$$

$$\xi' = \left(2 - \frac{c^2}{\beta^2}\right)\left[\eta_2'\phi \cos kh\eta_1 + \frac{1}{\eta_1}\left(\frac{c^2}{\beta'^2}\,\frac{\mu'}{\mu} - \phi - \frac{c^2}{\beta^2}\right)\sin kh\eta_1\right]$$

$$+ 2\eta_2\left[\left(\frac{c^2}{\beta'^2}\,\frac{\mu'}{\mu} - \phi\right)\sin kh\eta_2 - \frac{\eta_2'}{\eta_2}\left(\frac{c^2}{\beta^2} + \phi\right)\cos kh\eta_2\right]$$

$$\eta = \left(2 - \frac{c^2}{\beta^2}\right)\left[\eta_1'\phi \cos kh\eta_2 - \frac{1}{\eta_2}\left(\frac{c^2}{\beta'^2}\,\frac{\mu'}{\mu} - \phi - \frac{c^2}{\beta^2}\right)\sin kh\eta_2\right]$$

$$+ 2\eta_1\left[\left(\frac{c^2}{\beta'^2}\,\frac{\mu'}{\mu} - \phi\right)\sin kh\eta_1 - \frac{\eta_1'}{\eta_1}\left(\frac{c^2}{\beta^2} + \phi\right)\cos kh\eta_1\right]$$

$$\eta' = \left(2 - \frac{c^2}{\beta^2}\right)\left[\left(\frac{c^2}{\beta'^2}\,\frac{\mu'}{\mu} - \phi\right)\cos kh\eta_2 + \frac{\eta_2'}{\eta_2}\left(\frac{c^2}{\beta^2} + \phi\right)\sin kh\eta_2\right]$$

$$+ 2\eta_1\left[\eta_2'\phi \sin kh\eta_1 - \frac{1}{\eta_1}\left(\frac{c^2}{\beta'^2}\,\frac{\mu'}{\mu} - \phi - \frac{c^2}{\beta^2}\right)\cos kh\eta_1\right],$$

and where

$$\phi = 2\left(\frac{\mu'}{\mu} - 1\right)$$

and

$$\eta_1 = \left(\frac{c^2}{\alpha^2} - 1\right)^{1/2}, \qquad \eta_2 = \left(\frac{c^2}{\beta^2} - 1\right)^{1/2}$$

$$\eta_1' = \left(1 - \frac{c^2}{\alpha'^2}\right)^{1/2} \qquad \eta_2' = \left(1 - \frac{c^2}{\beta'}\right)^{1/2}$$

and the other symbols have the same meaning as before. Again we replace the α by V_p and the theoretical curves are shown in Figure 6. The computed points are tabulated in Table II. The constants were chosen to fit the case of Plexiglass overlying Panelyte. (See Table I.)

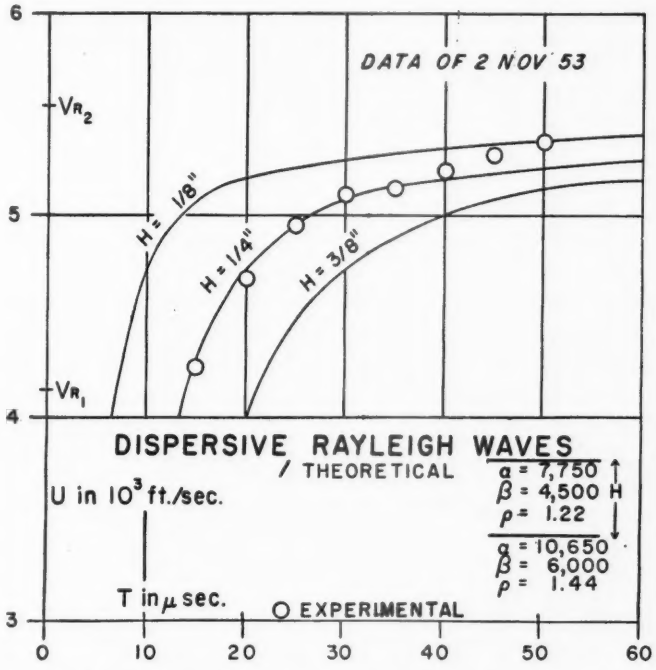

FIG. 6. Rayleigh wave dispersion—low velocity layer/high velocity substratum.

The disk was 19.522 inches in diameter with outside diameter of the outer ring $\frac{1}{2}$ inch greater. Figure 7 is a record taken at $\Delta = 180°$. Because of the small contrast between these two materials and the high attenuation in the plastic, more precision was obtained by using seismograms at several different Δ's rather than the one from the antipodes alone. As before, this eliminates the difficulty with the origin time of various periods in the pulse by making the velocity determination independent of pulse time. Figure 6 shows the experimental results in good agreement with the theory.

TABLE II

PHASE AND GROUP VELOCITY VS kH FOR A LAYER WITH $\alpha=7{,}750$ FT/SEC, $\beta=4{,}500$ FT/SEC, $\rho=1.219$ GM/CC OVERLYING A SEMI-INFINITE LAYER WITH $\alpha=10{,}650$ FT/SEC, $\beta=6{,}000$ FT/SEC, $\rho=1.436$

Computed values		Values obtained graphically		
c in ft/sec	kH	kH	U in ft/sec	c in ft/sec
5,535	0	0	5,535	5,535
5,500	.075	.05	5,488	5,510
5,450	.203	.1	5,449	5,490
5,400	.358	.2	5,379	5,453
5,530	.550	.3	5,323	5,418
5,300	.765	.4	5,276	5,388
5,200	1.152	.5	5,233	5,362
5,100	1.450	.75	5,123	5,302
5,000	1.722	1.00	4,987	5,241
4,900	1.955	1.25	4,766	5,168
4,800	2.196	1.50	4,543	5,083
4,700	2.425	1.75	4,283	4,977
4,600	2.689	2.00	4,020	4,838
4,400	3.392	2.25	3,842	4,973
4,300	3.965	2.50	3,685	4,672
4,200	5.107	2.90	3,623	4,528
		3.0	3,626	4,498
		4.0	3,770	4,296
		5.0	3,886	4,207

The Panelyte is anisotropic, having a velocity about $1\frac{1}{2}\%$ higher in one direction than in the perpendicular direction. This was not taken into account in the calculations and is a source of error in the comparison with the theoretical curves. The points for the two longest periods both fall high. These long periods can only be distinguished in the dispersive train after a considerable length of path has been traversed. At that time the amplitudes are low and, in fact, the relative am-

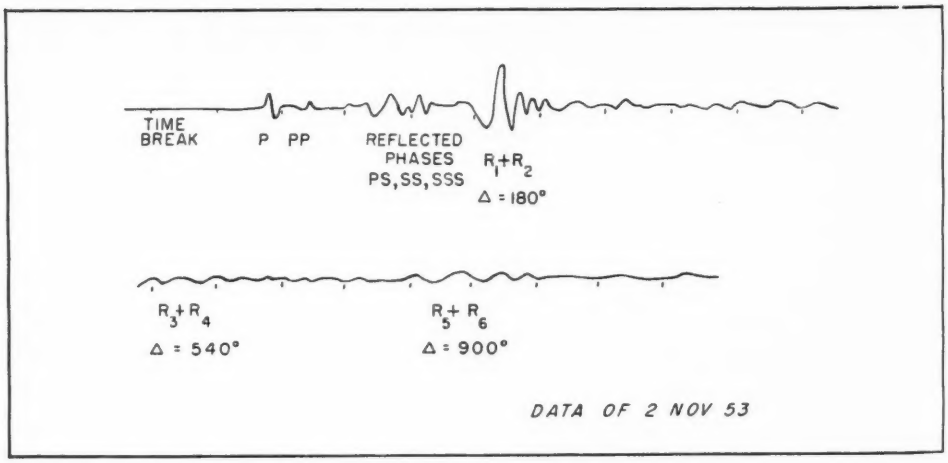

FIG. 7. Seismogram—low velocity layer/high velocity substratum.

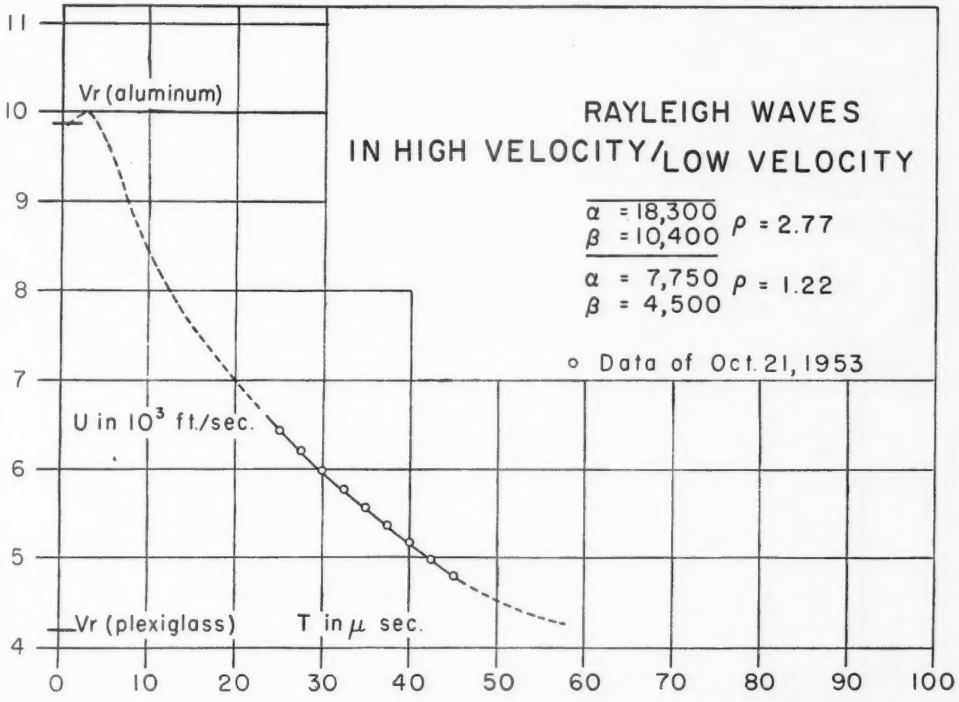

FIG. 8. Rayleigh wave dispersion—high velocity layer/low velocity substratum.

plitudes of such periods are always low due to the pulse shape. Thus the accuracy of velocity measurement is reduced for these waves. Furthermore, it is possible that these waves may be long enough to be affected by the curvature of the disk. The discrepancy is in the proper direction, but this effect has not yet been studied. At most, however, the error is 2%.

Experiments in higher mode Rayleigh waves (shear modes) and on Stoneley waves are planned.

Rayleigh Waves—High Velocity over Low Velocity

The previous examples have shown a comparison of experimental data with theoretical curves. In both cases the theoretical calculations were relatively simple and within the range of an ordinary desk calculator. In the case of a high velocity layer over a semi-infinite low velocity stratum the computations increase greatly in complexity. On the other hand, there is no difficulty in modelling this case. Figure 8 is a plot of the Rayleigh wave dispersion for the case of a ring of aluminum alloy overlying a disk of Plexiglass. Figure 9 is a tracing of the seismogram at the antipodes. The ring of aluminum is the same as that use for the flexural waves. This configuration corresponds to a layer of rock with elastic constants $\alpha = 18{,}300$ ft/sec and $\beta = 10{,}400$ ft/sec, overlying a semi-infinite layer with

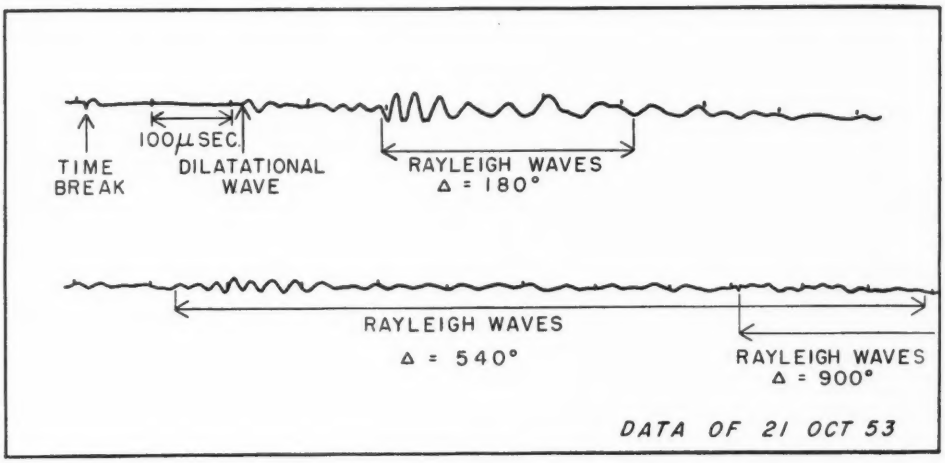

FIG. 9. Seismogram—high velocity layer/low velocity substratum.

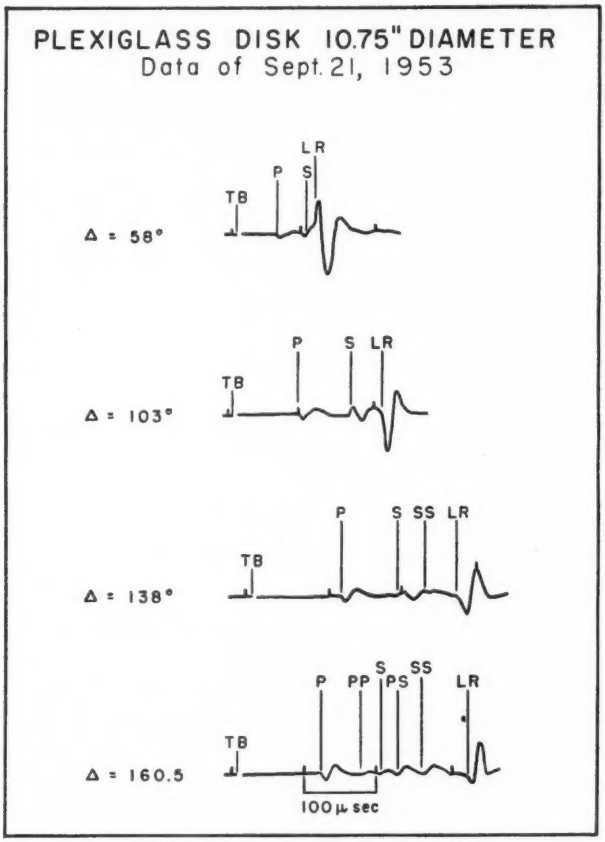

FIG. 10. Seismogram—Plexiglass disk.

$\alpha = 7{,}750$ ft/sec, $\beta = 4{,}500$ ft/sec. The ratio of the densities is $\rho/\rho' = 2.77/1.22$. This is a fair approximation to the case of Palisades diabase overlying Triassic sandstones and shales along the west bank of the Hudson River. It is also similar to structure in the permafrost areas in the Arctic.

Because of the limited spectrum of the pulse only a portion of the complete dispersion curve is obtained. Other segments may be studied by varying the thickness of the layer.

Body and Surface Waves in Disks

The previous examples, all concerning surface waves, used wavelengths which were small enough compared to the curvature of the disks so that the waves were effectively traveling along flat surfaces. Disks were chosen merely as a

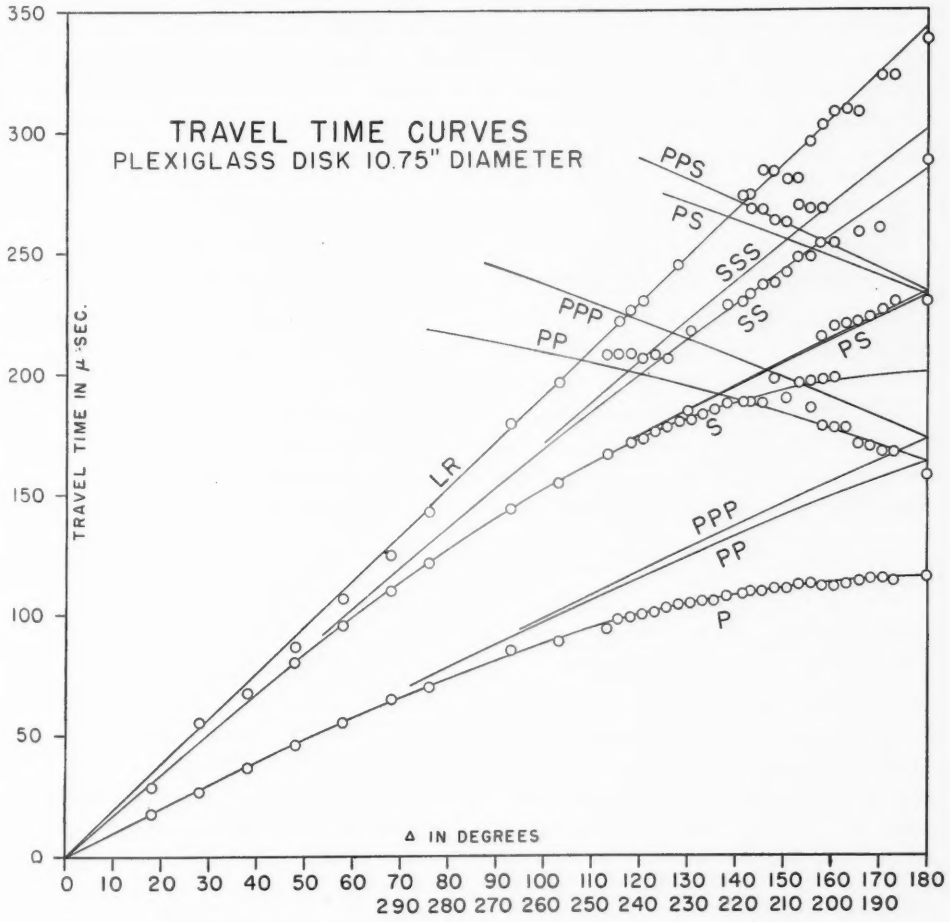

FIG. 11. Travel time curves—body and surface waves in a disk.

convenient shape to work with because of the multiple paths and lack of surface wave reflections. However the disk as a two-dimensional model of the earth also appears promising for the study of body waves. The seismograms of Figure 10 were taken on a uniform Plexiglass disk of diameter 10.75 inches. Figure 11 is a plot of the experimental points read from the records, compared with theoretical travel time curves based on velocities determined from the *P* arrivals. Poisson's ratio is taken as $\frac{1}{4}$. Phases definitely identifiable are *P*, *PP*, *S*, *PS* and *PPS*, *SS*, and *LR*. At the larger Δ's there is some difficulty in determining the exact arrival time and phase of the later arrivals due to overlapping of other phases. The present picks for the later arrivals are nearly always late. Clearly, this can be avoided by the use of larger disks and future studies will be made on disks of at least twice this diameter. This should improve the resolution of phases and accuracy of the arrival times measurably.

The polarity of the first break of the Rayleigh wave changes with distance. Such is not the case for Rayleigh waves propagating along the straight edge of a plate, which rules out the possibility of selective absorption of the high frequencies as the cause. The change of polarity is possibly the result of the generation of the waves by the curved *P* and *S* wave fronts at the surface. The phenomenon is not understood at present.

Scaling to Related Problems

The dispersion curves of the preceding examples are presented in the dimensions as modeled. Scaling to other problems is a relatively simple matter, as can be seen from an inspection of the period equation for flexural waves or Rayleigh waves. Once a fixed relation is established between all the dilatational and shear velocities the equations may be solved for the ratio c/β or c/α and similarly U/β or U/α. Thus velocities may be scaled to any other problem for which the elastic constants have the same ratios merely by multiplying the measured velocities by the appropriate ratio β'/β or α'/α. Similarly, the period associated with a given phase and group velocity will vary directly with H, the layer thickness.

ACKNOWLEDGMENTS

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The Carter Oil Company generously gave assistance in the design of circuits used, through Dr. Franklyn Levin, who participated in the seismic model work for that company.

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A THREE-DIMENSIONAL SEISMIC WAVE MODEL WITH BOTH ELECTRICAL AND VISUAL OBSERVATION OF WAVES*

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ABSTRACT

The short wave lengths required in a seismic model to give wave-front patterns geometrically similar to those in a large prototype (the earth) can only be obtained by using high frequency sound waves. As sources and detectors of such high frequency waves, piezoelectric crystals are used, primarily because under identical stimuli they are capable of almost perfect duplication. Such duplication is made use of in displaying on an oscilloscope stationary patterns which are characteristic of transient particle motion at a point in the model. Also, it has made possible the direct visual observation of transient wave fronts in transparent models, techniques for which are described, and sample photographs given. As an example of quantitative use of the described model techniques, the results are presented showing symmetric and anti-symmetric wave propagation in a free elastic plate. Good agreement is found between many features of the experimental record and theoretical predictions.

INTRODUCTION

Seismic exploration research has, during the past few years, experienced a shift of emphasis from instrumental development to the more fundamental aspects of the seismic process. Geophysicists have come to realize the meagerness of their knowledge of the various factors affecting the generation and transmission of seismic waves. Experiments dealing directly with the transmission of acoustic waves within the earth are difficult if not impossible to carry out. Consequently, parallel studies have been undertaken in the laboratory using scaled-down models of the earth.

In setting up such models, a number of instrumental problems have been encountered. This paper will deal with some of the techniques thus far developed to meet them. Methods will be described for displaying and recording the motion of a point on or in the model resulting from application of an acoustic impulse at some other point, as well as for rendering directly visible transient wave fronts within transparent materials. In addition we shall present some preliminary results, both qualitative and quantitative, obtained with our models.

INSTRUMENTATION

In designing a seismic model for representing wave processes on a reduced scale, it is obvious that the wave patterns produced therein should be made geometrically similar to those of the prototype if their correspondence is to be established and made the basis for predicting phenomena in the prototype. Accordingly the wave-length scale must be reduced in the same ratio as the linear dimensions.

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If the earth is the prototype, then the scale factor must be large. However, no solid materials are available which have elastic wave velocities substantially less than those of the earth. Therefore, the only practical way of producing short wave lengths is to use high frequencies. Piezoelectric crystals have been used almost entirely as elastic wave sources and detectors in the work carried on thus far.

Display System

The first problem encountered in the electromechanical detection of wave motion in a model is how to display a short acoustic transient. This problem is readily solved by making use of two facts: 1) that a piezoelectric crystal when successively pulsed in the same way will duplicate its acoustic output very

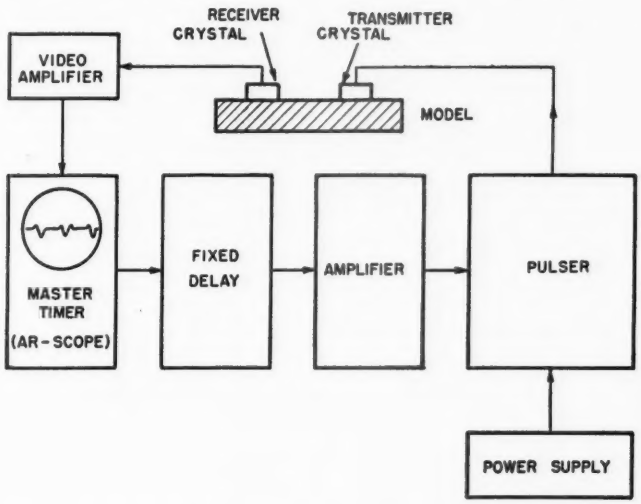


FIG. 1. Block diagram of circuit for electrical observation of acoustic waves in models.

closely; 2) that in a small block of material a single acoustic pulse can be reflected a number of times and finally totally absorbed, all within a small fraction of a second. That is, an individual wave event can be repeated up to several hundred times a second without overlap. Then, by properly synchronizing the sweep of an oscilloscope to the initiating electrical pulse and repeating this operation many times per second, a visible stationary oscilloscope trace can be obtained whose form is characteristic of the transient particle motion at the detector point.

Figure 1 shows a block diagram of the entire system. The equipment was made up from a number of war surplus radar components. Actually, it provides only for recording the output of one detector at a time. Multiple trace records can be obtained, however, by rotating the film of the recording camera by a constant amount between exposures. Each exposure is made for one position of the single

detector, which can be moved between exposures to different positions on the model as required.

Transducer Design

A difficult problem in working with wave models is how to produce and detect short simple pulses of distinctive form, with piezoelectric crystals. An isolated piezoelectric crystal when activated either by an electrical or an acoustical pulse tends to reverberate within itself. It will also do so when in direct contact with another material whose acoustic impedance is different from its own. If, however, the crystal is in direct contact at one face with a substance having an acoustic impedance the same as its own, then elastic pulses will pass through this interface

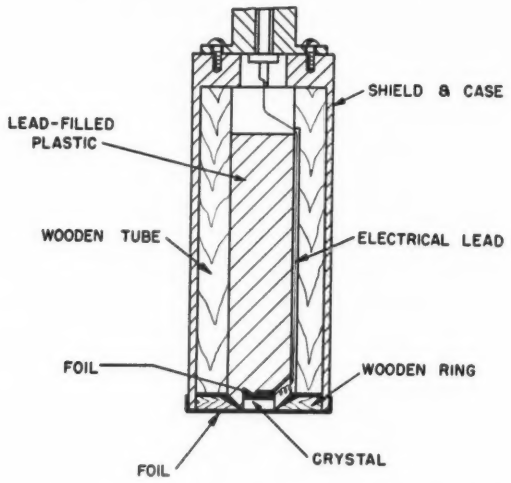


FIG. 2. Cutaway view of piezoelectric transducer used in wave model experiments.

without reflection and reverberation will be prevented. In general, it is desirable to provide a crystal transducer with a "backer" having an acoustic impedance matching that of the crystal in order to prevent the complication of single pulses by reverberation. It was also found advantageous in many cases to provide "edge-damping" as well as "face-damping."

Figure 2 shows an optimized design of holder for either a wave source or detector crystal. The crystal most favored is lithium sulphate monohydrate ($LiSO_4$-H_2O), which combines the desirable properties of high sensitivity, relative purity of wave form, and some internal damping. The backing material, which also extends around the edges of the crystal to provide edge-damping, consists of plastic filled with lead powder. The wooden tube surrounding the backer and the wooden ring near the end of the holder are for the purpose of isolating the crystal and its backer from waves entering from the sides or the back. Foil electrodes cover the

back and front faces of the crystal, and are solidly bonded to it and to the plastic backer by means of polymerized plastic glue.

A MODEL REFLECTION RECORD

Figure 3 shows a 6-position reflection record made with a block of Ward's Bio-Plastic about two inches thick and a foot square. Both wave source and detector were on the same side of the block. The horizontal distance of the detector was successively increased in steps of one centimeter between exposures. The time markers shown at the top and bottom of the record are at 10-microsecond intervals.

The first line of peaks marked "*L*" corresponds to the arrival of the first direct

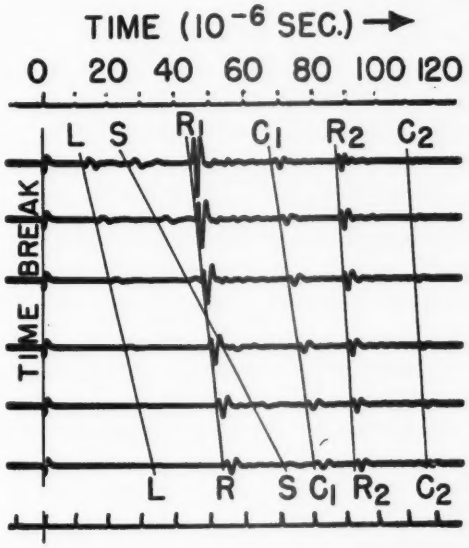


FIG. 3. Reflections in a 2.15-inch thick plate of Ward's "Bio-plastic."

longitudinal wave. Its slope gives the velocity of body compressional waves in the plastic. The next sloping line, marked "*S*," shows the arrival of a surface wave. The peaks marked "R_1" comprise the first longitudinal reflection from the bottom of the block, and those marked "R_2" indicate the first multiple longitudinal reflection.

The peaks marked "C_1" require a little more explanation. They are caused by *PS* or *SP* reflections in which a pulse travels down, say, in the form of a longitudinal wave, and is transformed by reflection into a transverse wave. Or a transverse wave could be transformed into a longitudinal wave; the travel time would be the same. In fact, such peaks are due to the superposition of waves which have traveled both of these possible paths. The peaks marked "C_2" comprise a multiple reflection for which the reflection path includes three longitudinal wave seg-

ments and one transverse wave segment. In effect, this reflection is a superposition of four such combinations, *viz. PPPS*, *PPSP*, *PSPP*, and *SPPP*. All of these combinations have identical travel time. The multiple reflection combinations involving two or more transverse wave segments are too weak to be observable.

In many cases it is desirable to have longer or more detailed records, which can be obtained by making use of one of the so-called range, or expanded, sweeps of the *AR*-scope. Although such expanded sweeps can only be displayed one part at a time, the characteristic stationary pattern can be made to move continuously across the screen, or stopped with any desired section on display, by turning the control knob of the variable delay circuit. The timing marks, which are pips or dots superimposed from a crystal oscillator circuit, can also be made to move along with the pattern. For the expanded sweep most often used in our work, about twenty-five microseconds of sweep can be shown at one time.

VISUAL OBSERVATION OF WAVES

The electromechanical detection of wave motion in a model as so far described corresponds to the standard seismograph method of recording wave motion of the earth. The actual wave patterns and transmission paths in the model must still be inferred through the component motions imparted to detectors placed at several points. It would be a material help, however, in sorting out and

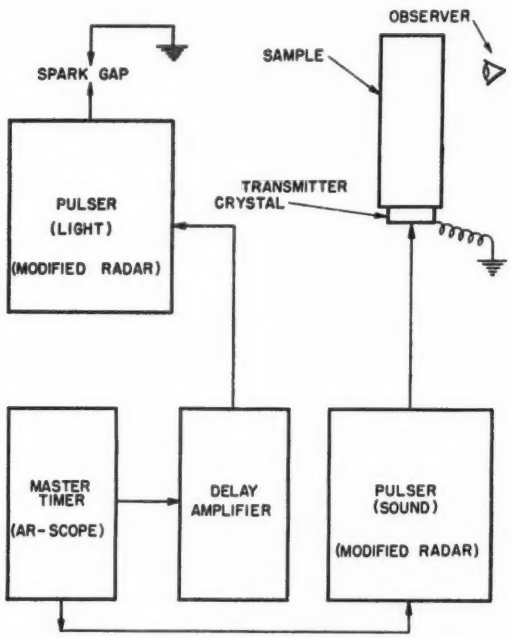


FIG. 4. Block diagram of circuit for visual observation of acoustic wave fronts in transparent models.

identifying the various waves present with respect to position, travel direction, and type, if they could be made directly visible in transparent materials.

To do this it is necessary not only to render the waves visible but also to "stop" them. The latter operation involves illuminating the model stroboscopically with very short and precisely timed flashes of light. Longitudinal waves travel in most plastics at a speed of about 9,000 feet per second. In order to "stop" a wave traveling at such speed with a blur not to exceed 1/32 inch, it must be illuminated by a flash not longer than 0.3 microseconds. Here again, in order to obtain a steady pattern from an essentially transient phenomenon, events were closely duplicated hundreds of times per second.

Figure 4 shows a block diagram of the circuit. Each electrical pulse applied to the sound source triggers, with accurately constant time delay, another pulse which in turn triggers an electric spark. The light from this spark then "catches" each successive duplicate wave pattern when it is the same distance out from the sound source. The time interval between application of the sound pulse and the flashing of the light must be kept constant to within the same limit of accuracy as the total duration of the spark, that is, to within 0.3 microseconds. The trigger and variable delay circuits of *AR*-scopes are used for generating, controlling, and timing the various required pulses.

Next, in order to render the waves, once stopped, actually visible two well-known optical methods were used.

The first technique, diagrammed in Figure 5, makes use of the phenomenon of photoelasticity. It is a property common to many transparent materials that, when stressed, they acquire the property of becoming double refracting. If a block of such material is placed between two "crossed" polaroid films and viewed by light transmitted through the system, the stressed regions become visible.

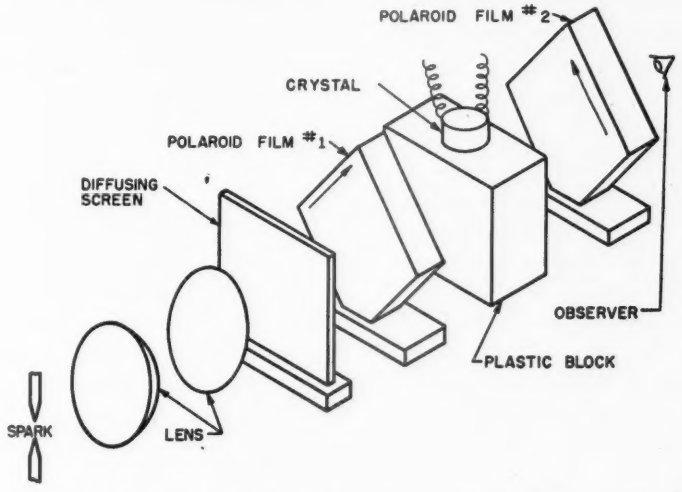


FIG. 5. Setup for visual observation of wave fronts in transparent models by means of photoelasticity.

The method applies only to solids, in which both compressional and shear waves can be made visible. In Figure 5 the light from the spark source is condensed into a parallel beam. The diffusing screen creates a uniform field of illumination. The plastic block is interposed between two polaroid films which are set up with their planes of polarization rotated by 90° with respect to each other. The combination of the two polaroid films is rotated by 45° with respect to vertically traveling wave fronts in the plastic, thereby accentuating longitudinal waves. The combination of polaroids would be rotated by an additional 45° to give maximum visibility to transverse waves.

The other technique used to render wave fronts visible is that of the so-called schlieren method. It is applicable to all transparent media, liquids as well as solids,

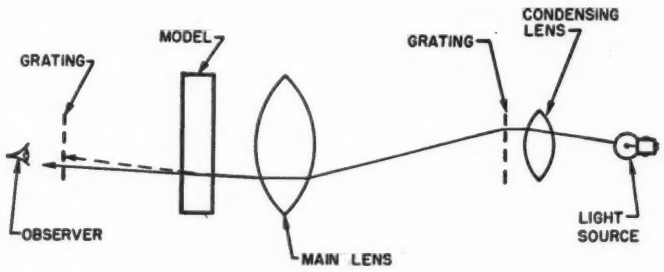


FIG. 6. Setup for visual observation of wave fronts in transparent models by means of multiple-slit schlieren system.

but will not show shear waves. In the simplest type of schlieren apparatus, a slit source of light is sharply focused upon a knife edge, with the optical path traversing the object to be viewed. Density gradients within the volume of this object (or elsewhere between the slit and knife edge), however generated, will deflect more or less light to the analyzing knife edge by virtue of acting as weak refracting prisms. Such regions of density gradient are then visible to an observer whose eye is behind the knife edge, appearing darker or lighter than neighboring regions. In this work, a more modern version was used in which coarse gratings effectively serve as multiple slit sources and analyzing obstructions (Mortensen, 1950; Burton, 1951). This grating method is shown schematically in Figure 6.

PHOTOGRAPHS OF REFRACTED WAVE FRONTS

Figure 7 shows a setup used in observing and making photographs of traveling wave fronts by the schlieren method. The model consists of a Plexiglass plate with an oil layer above it, the oil being confined by a parallel-faced glass tank. A piezoelectric crystal with backer is pressed against one corner of the plastic plate.

Figure 8 is a schlieren photograph taken through the upper part of the plexiglas plate and the overlying layer of oil. It shows a longitudinal wave front advancing along the edge of the plate at grazing incidence to the solid-liquid bound

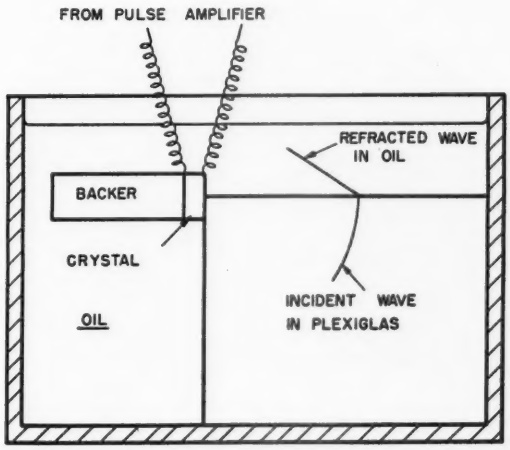


FIG. 7. Model used for the visual observation of the refraction of waves incident on a boundary at grazing angle.

ary, and being refracted into the liquid above. If the field of view were larger, it could be seen that the incident wave front in the plastic is circular, or nearly so, in profile. It is apparent, however, that the refracted wave front in the liquid has a straight profile, as if generated by the advance of a center of disturbance along

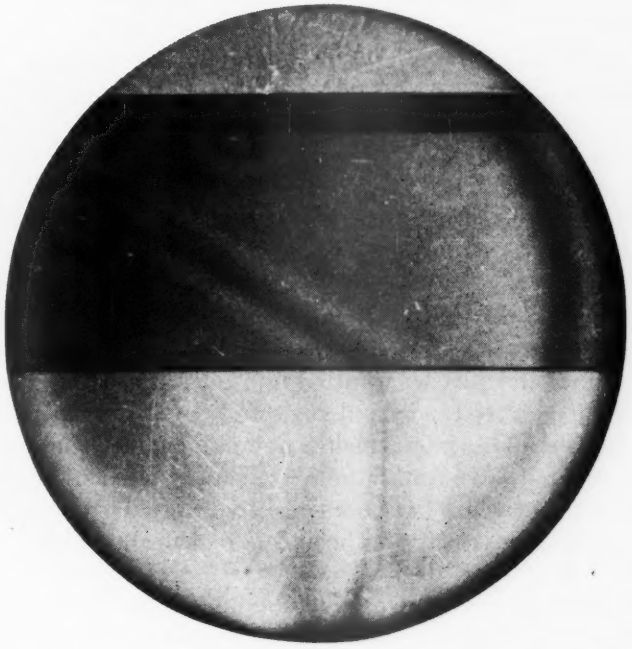


FIG. 8. Schlieren photograph of wave front being refracted from Plexiglass into oil.

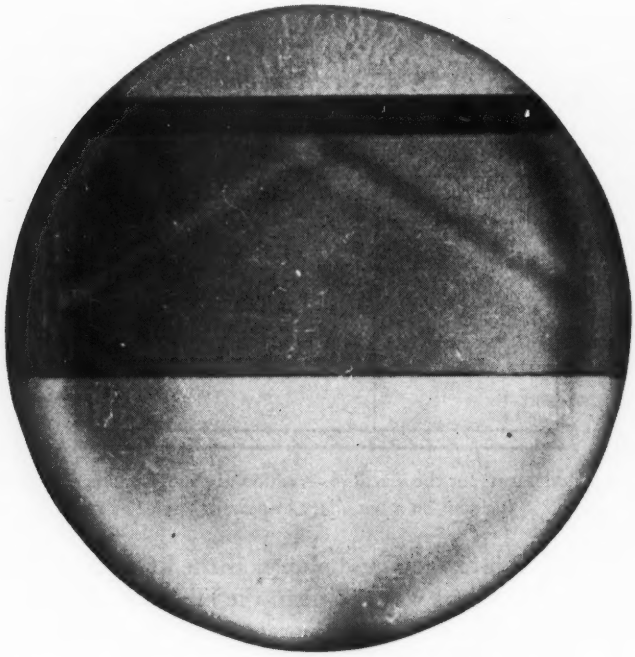


FIG. 9. Schlieren photograph of wave front being reflected from free surface of oil.

the boundary (Schmidt, 1938). The angle between the refracted wave front and oil-plastic boundary is closely equal to the critical angle for these materials.

The photograph of Figure 9 was taken with an increased delay between the application of the acoustic pulse in the model and the illuminating spark. It shows the straight-profiled, refracted wave front in the liquid as it is being reflected back from its free surface. The angle of reflection is plainly equal to the angle of incidence; and by close inspection, it can be further seen that a phase change of 180°, predicted by simple theory, has occurred at the free boundary.

The final picture in this sequence, Figure 10, shows the once-reflected wave front as it again encounters the liquid-solid interface. Part of it is being reflected back into the liquid, and part transmitted into the solid. Although the angle of incidence is closely equal to the critical angle and the refracted *ray* if any should be practically parallel to the interface, it is of interest to note the apparent penetration of the refracted wave front into the solid. The other waves in the upper, liquid medium are those which have been directly transmitted through the liquid, which has a propagation velocity for body compressional waves lower than that of the plastic.

An optical model such as was used in obtaining these photographs must be relatively thin in the direction in which the light is transmitted. However the additional wave fronts resulting from reflections at the front and back faces of the

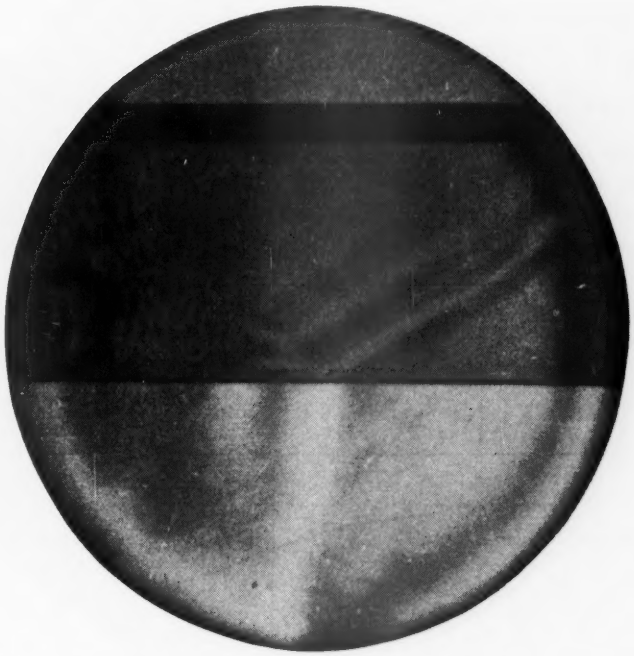
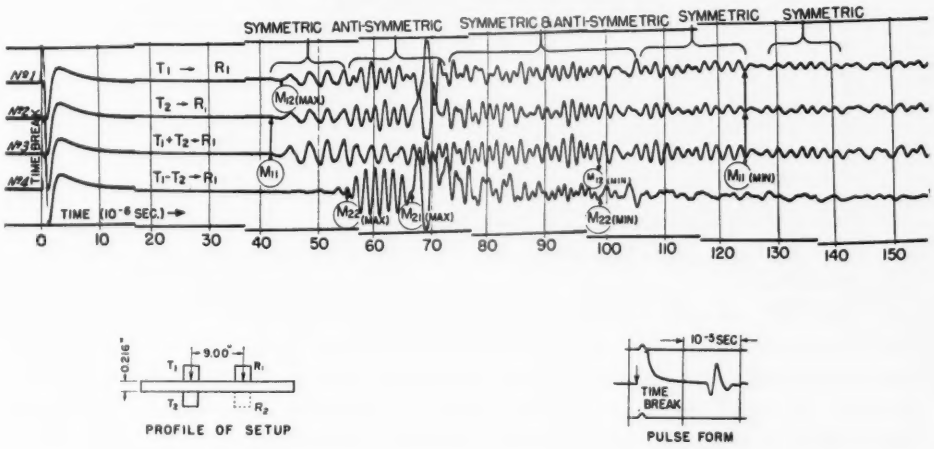


FIG. 10. Schlieren photograph of wave front being in part reflected and in part refracted at oil-Plexiglass interface.



SYMMETRIC AND ANTI-SYMMETRIC PULSE TRANSMISSION IN GLASS PLATE (POISSON'S RATIO = ~0.25)

FIG. 11. Record, assembled by piecing, which shows symmetric and anti-symmetric pulse transmission in a glass plate.

model do not become visible because they are not tangent to any line of observation, i.e., are not viewed in profile.

SYMMETRIC AND ANTI-SYMMETRIC WAVE MOTION IN PLATES

In order to test whether the wave model techniques so far described are capable of giving results in accord with theory under conditions amenable to exact mathematical solution, experiments were performed on the propagation of pulses in free elastic plates. The general solution, i.e. the so-called period equation for

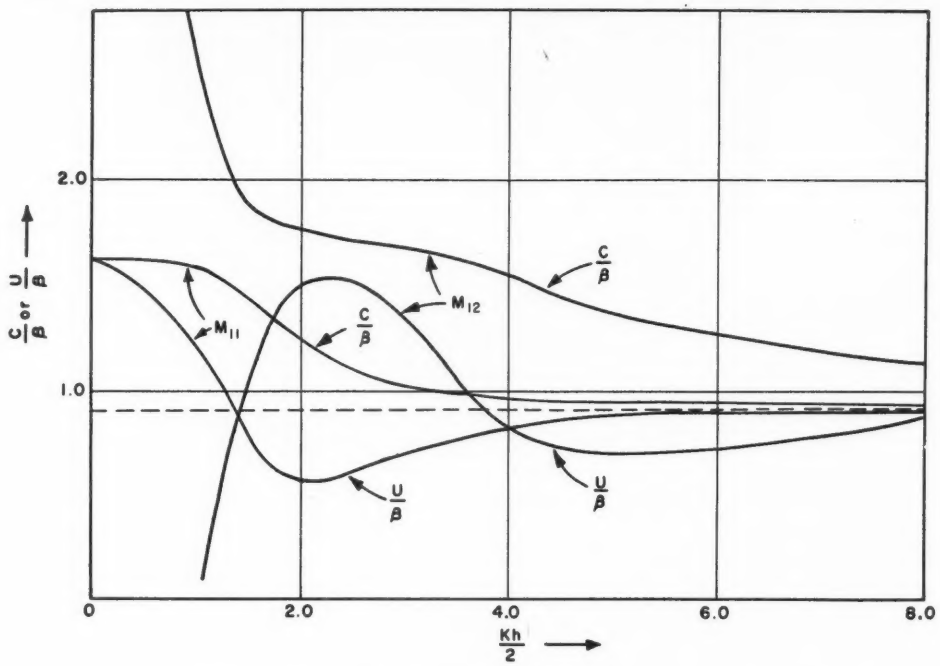


FIG. 12. Dispersion curves for symmetric modes in free elastic plate. (After Tolstoy and Usdin, Geophysics, v. 18, p. 850, October, 1953.)

this case was first given by Horace Lamb. It has been re-derived by Tolstoy and Usdin (1953) using a different method. Tolstoy and Usdin use this case of the free elastic plate as an example for confirming the applicability of an interference principle to the general problem of waves in stratified media. Their Figures 3 and 4 are here reproduced as Figures 12 and 13, respectively.

In the curves of Figures 12 and 13, the ordinates represent phase velocity c and group velocity U expressed as nondimensional ratios c/β and U/β respectively, where β is the velocity of shear body waves. The abscissa are $kh/2$ which is also a nondimensional quantity in which $k = 2\pi/\lambda$, λ being the wave length and h the thickness of the plate. The phase velocity c is the instantaneous velocity in the direction of propagation of a point of constant phase, such as a peak. The

group velocity U represents the speed of propagation of the energy corresponding to a given frequency. There are two types of propagation. One of these corresponds to deformations of the plate which are symmetric with respect to its median plane (M_{11}, M_{12}, M_{13}, M_{14}, etc.). The other corresponds to deformations which are anti-symmetric with respect to the median plane of the plate (M_{21}, M_{22}, M_{23}, M_{24}, etc.). Each of these types of propagation is characterized by fundamental and harmonic modes, of which there are infinitely many. Only the fundamental and the first harmonic have so far been numerically calculated, however,

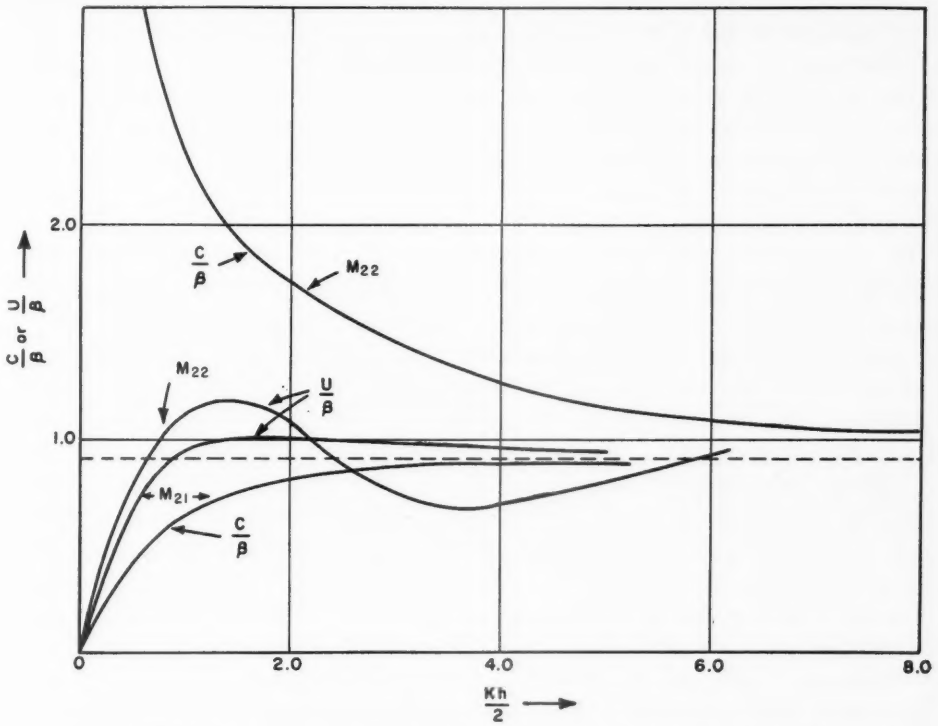


FIG. 13. Dispersion curves for antisymmetric modes in free elastic plate. (After Tolstoy and Usdin, Geophysics, v. 18, p. 851, October, 1953.)

and are shown in the figures. In calculating these curves, a specific value of 0.25 was assumed for Poisson's ratio.

The record of Figure 11 was obtained with the physical setup schematically shown in the lower left hand corner by the inset sketch. This record is not a simultaneous recording of several concurrently operating traces but is a synthetic, two-dimensional patchwork of separate exposures. Thus Figure 11 consists of 48 exposures altogether, grouped in eight 20-microsecond sections of six exposures each. Each section is an exposure sequence made without changing the delay adjustment, so that the same time interval of the record is on display on each trace

throughout the section, and adjacent recorded traces are directly comparable with respect to time, i.e., vertical lines are lines of equal time. That such a patchwork when finished can represent real wave processes occurring in the model depends, of course, on the fact already mentioned, that the same wave process can be repeated many times with almost perfect duplication.

Two identical piezoelectric transducers of design similar to that of Figure 2 (except that the active crystal material had the shape of a long narrow prism $\frac{1}{8}\times\frac{1}{8}\times\frac{1}{2}$ inches) were oppositely pressed against a glass plate 0.216 inches thick. Glass was selected as the plate material because it has a Poisson's ratio quite close to 0.25, the value assumed in computing the curves of Figures 12 and 13. The wave sources were purposely made narrow to simulate line sources, and when electrically pulsed, imparted a motion normal to the plate. A single receiver, similar in design and shape to the sources, was set up on one side of the plate. The distance of separation between center lines of receiver and sources was 9.00 inches, and the long axes of all transducers were oriented at right angles to the path of direct transmission. The glass plate was of such size that the shortest reflection path to the plate edges was 3.3 times as long as the direct path. The lower right hand inset of Figure 11 shows the pulse form transmitted between a similar transmitter and receiver correspondingly located on a much thicker plate.

The top and bottom traces of Figure 11 contain time markers spaced at regular intervals of 10 microseconds through which connecting lines were drawn. The trace marked No. 1 shows the output of the receiver R_1 with the acoustic source T_1, on the same side of the plate, active. Trace No. 2 shows the output of R_1 with the source T_2, on the opposite side of the plate from R_1, active. Due to symmetry, a virtual receiver R_2 placed on the opposite side of the plate from R_1 but with T_1 active as the source, will have the same output as receiver R_1 with source T_2 active, i.e., the output of virtual receiver R_2 will still be represented by trace No. 2. Due to problems of electrical shielding, it is more convenient to use two sources and one receiver than two receivers and one source.

Comparing trace No. 1 ($T_1 \rightarrow R_1$) and trace No. 2 ($T_1 \rightarrow R_2$ or $T_2 \rightarrow R_1$), it appears that over the intervals in which the traces are similar and in phase, oppositely situated surface particles move outward simultaneously from the median plane of the plate. In other words, the motion resulting from a normal impulse applied to one side of the plate is *symmetric*. Also, over those intervals in which the traces are similar in form but out of phase, oppositely situated particles simultaneously move up and down together. In other words, the motion is predominantly *anti-symmetric*. In the case of purely symmetric wave motion, one may picture *bulges* as moving along the plate and, for anti-symmetric wave motion, *flexures*.

Trace No. 3 shows the output of R_1 when T_1 and T_2 are simultaneously pulsed in phase. By superposition, this trace is equal to the algebraic sum of traces 1 and 2. Over those intervals in which the wave motion indicates symmetrical vibration of the plate, trace 3 reproduces the character of either trace 1 or 2, except with

larger amplitude. In those intervals in which the motion of traces 1 and 2 indicates anti-symmetric vibration of the plate, trace 3 should indicate a minimum of amplitude. Examination of the record indicates that this situation is substantially observed. In the predominantly anti-symmetric intervals, trace 3 is not entirely dead. This indicates either that there is some symmetric motion present in these intervals, or that there must be some differences in the nature, assumed identical, of the sources, or, possibly that some intervening non-symmetrical inhomogeneities exist in the material of the plate. From a different viewpoint, if T_1+T_2 is considered as a single symmetrical source, then trace 3 would represent the output of R_1 when the plate is pulsed by this source. Likewise, if T_1-T_2 is considered as a single anti-symmetrical source, then trace 4 would represent the response of R_1 to a pulse of this source.

Keeping in mind the distinction between symmetric and anti-symmetric motion of the plate, there is a number of prominent features shown on the record of Figure 11 which theoretically should be correlatable with corresponding features of the theoretical dispersion curves of Figures 12 and 13. At the present time, only the fundamental and first harmonic modes of the dispersion curves have been calculated for the symmetric and anti-symmetric types of wave motion. Some of the prominent features of the record of Figure 11 may be due to higher order modes of vibration and would need calculation of additional curves for their identification. However, there are three important features which are fully correlatable with corresponding features of the dispersion curves. The first event on the record of Figure 11, to be considered, is the large anti-symmetric pulse marked M_{21} (max) on trace No. 4, at a time of 66.5 microseconds. The travel time from the application of the pulse to the onset of this feature corresponds to a velocity of 11,000 feet/second. By independent measurement on a thick block of glass, this is found to equal (within 2%) the velocity of shear body waves in the material. Inspection of Figure 13 for the group velocity curve, U/β, of the first anti-symmetric mode, M_{21}, shows a very broad maximum. For a given plate, the thickness h is constant and $k/2$ increases with the frequency. The broad maximum therefore means that a wide band of frequencies is transmitted with substantially the same velocity. This is the condition for transmitting a pulse with small distortion. In Figure 13 the maximum value on this curve for U/β is shown to be 1.00, indicating that for those frequencies in the range of this broad maximum, the velocity of travel is equal to the shear velocity in the plate material. The travel time to event M_{21} (max) indicates a velocity of propagation equal (within 2%) to β. Therefore, the large pulse of trace 4 can be definitely identified with the maximum of the group velocity curve M_{21} of the theoretical dispersion curves.

The next event to be considered, M_{22} (max), is an oscillatory wave group occurring at a time of about 55 microseconds on the anti-symmetric trace No. 4 of Figure 11. The presence of this feature would hardly be suspected from the observation of component traces No. 1 and No. 2, and it is quite small on the symmetric trace No. 3. By measurement on the record, the onset of this group M_{22}

(max) occurs at a time which corresponds to a velocity of propagation of 1.20 β. Referring to Figure 13, the group velocity curve U/β for the anti-symmetric mode M_{22}, shows a maximum at a velocity equal to 1.17 β. Furthermore, the maximum of this group velocity curve occurs at a frequency determined from the dispersion curves of about 6×10^5 cps. The frequency of this feature on trace No. 4 is about 5.5×10^5 cps which is in substantial agreement with theory. Thus, on the basis of frequency and velocity, the feature M_{22} (max) on the record is shown to correspond quite closely to the maximum of the dispersion curve of Figure 13. The frequency may be determined from the dispersion curves of Figures 12 and 13 and the plate constants h and β from the relations

$$f = c/\lambda = kc/2\pi \equiv (kh/2)\cdot(c/\beta)\cdot(\beta/\pi h).$$

The last of the three principal features of the record of Figure 11 is the first observable arrival on traces 1, 2, and 3, occurring at a time of 42 microseconds. This arrival is entirely absent on trace 4 and is therefore due to a symmetric wave. This arrival is characterized by low frequencies, and corresponds to the intercept of U/β as $kh/2\rightarrow0$. On the basis of this interpretation the theoretical velocity of this group should have a value of 1.63 β or less. Actual measurements on trace 3 of Figure 11 show this velocity to be 1.59 β.

On the basis of travel time and frequency, it has been shown that there is a very close correspondence between three principal features of the record of Figure 11 and the theoretical dispersion curves of Figures 12 and 13. In a similar

TABLE I

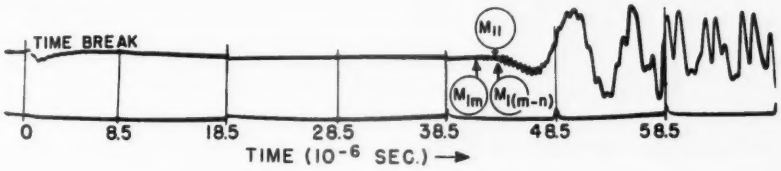
CORRELATION BETWEEN THEORY AND EXPERIMENT IN WAVE PROPAGATION IN A FREE ELASTIC PLATE

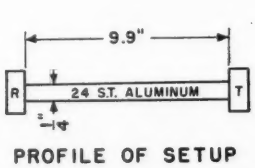
EXPERIMENTAL FEATURE				NEAREST CORRESPONDING THEORETICAL FEATURE			
Description	Time on Fig. 11, 10^{-6} sec.	Veloc. in terms of β	Freq. $\times10^{-5}$	Mode	Part of curve	Veloc. in terms of β	Freq. (calc.) $\times10^{-5}$
SYMMETRIC (Trace 3)							
1st arrival	42.0	1.59*	low	M_{11}	start	1.63	0
Start of "riders"	43.8	1.52	5–6	M_{12}	max.	1.55	7
End of high freq. group	98.0	0.68	8	M_{12}	min.	0.70	13
End of a group	124.7	0.54	5	M_{11}	min.	0.56	5
ANTI-SYMMETRIC (Trace 4)							
Start of oscillatory group	55.0	1.20	6	M_{22}	max.	1.17	5.5
Large ampl. pulse	66.5	1.00	4	M_{21}	max.	1.00	3
End of high frequency	99.0	0.67	10	M_{22}	min.	0.68	9

* Experimentally determined velocities have a maximum error of ±0.03 units.

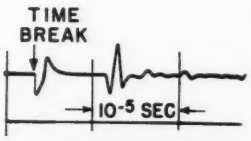
manner a number of other agreements, somewhat less positive than those already discussed, can be found between the experimental record and the theoretical curves. Some of these have been tentatively marked on Figure 11 and have been summarized in Table I.

In addition to the features of the experimental record which have been discussed, there remain a good many others which at present cannot be identified on the basis of the curves in Figures 12 and 13. Judged on a frequency basis, some of these features may be associated with the sloping parts of the curves, while others probably correspond to still higher modes which so far have not been numerically calculated.





PROFILE OF SETUP



PULSE FORM

FIG. 14. High-frequency fore runners in edge-to-edge transmission through 24 S.T. aluminum plate.

Figure 14 concerns the transmission of waves by a free elastic plate, and it is offered in experimental confirmation of a phenomenon predicted in a footnote of the paper of Tolstoy and Usdin (1953, p. 850). The record was made according to the experimental setup shown in profile by the insert. This might be called edge-to edge transmission through a plate. The material used in obtaining this record was aluminum. When a glass plate was used, the phenomenon did not appear, presumably due to absorption by the glass of the higher frequencies. The pulse form shown at the lower right is the one which was transmitted between the same two transducers when applied to opposite faces of a much thicker aluminum plate.

The point of main interest in Figure 14 is the high frequency forerunner, or group, whose onset precedes the low frequency break ascribed to M_{11}. These forerunners correspond to higher symmetric modes, M_{13}, M_{14}, etc., not specifically calculated thus far, but whose dispersion curve maxima are known to approach, with increasing mode number, that velocity which is characteristic of compres-

sional waves in extended media of the same material. To quote from Tolstoy and Usdin's footnote:

> For increasing mode number . . . both this maximum and the corresponding phase velocity tend to α [the velocity of compressional body waves in the same material]. Thus a discretely spaced set of high frequencies will propagate with velocities approximating that of P waves.

The record of Figure 14 plainly shows at least two member groups of the set, designated as starting at M_{1m} and $M_{1(m-n)}$, where $m>n$. The independently determined value of α for aluminum is 21,000 feet per second. The velocity of the first observable high-frequency energy on Figure 14 is 20,500 feet per second, which is close to, but nevertheless a little less, than 21,000 feet per second. This is in agreement with the theory.

CONCLUSION

Several problems remain unsolved in connection with the recording and display of seismic phenomena as simulated in scale models. One has to do with providing a point source of acoustic waves. Piezoelectric wave sources have finite size and consequently wave fronts produced by them are bound to depart somewhat from sphericity. Also waves of greater intensity than those employed in this work are needed in order to make possible direct visual observation of waves in complex models in which amplitudes may be greatly attenuated by diffraction, multiple partial reflection, absorption, etc.

In conclusion, it may be remarked that model work is designed to supplement both field and theoretical studies of a fundamental nature which relate to seismic prospecting. Through model studies, we hope to reach a better understanding of complex wave phenomena as they actually occur in the earth, and ultimately to solve some of the seismic problems presently confronting geophysicists.

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DEVICES FOR THE CONSTRUCTION OF REFRACTED RAYS*

RAOUL VAJK†

ABSTRACT

Simple devices constructed from such readily obtainable items as triangles, protractors, plastic rulers, and steel straight edges are described for the graphical solution of two problems which often arise in seismic computations. One problem is to find the minimum-time path between two points located in media with different seismic velocities separated by a plane interface. The other is to find the refracted ray where the incident ray to an interface and the velocities of the media on either side are known.

A problem frequently encountered in seismic computation is to find the path with minimum travel time between two points, S and G, located in media with different seismic velocities (Fig. 1).

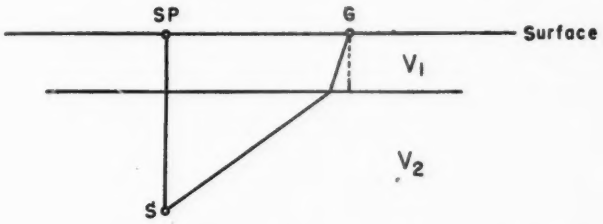

FIG. 1. Minimum travel-time path from S to G across the interface.

The analytical solution of this problem is rather complicated, and it is customary to solve it by trial and error, which is a lengthy procedure. With the aid of a simple device shown in Figure 2, this problem can be solved graphically without difficulty.

This device consists of a triangle A and two plastic rules B and C. A slot is cut parallel to one side of the triangle. Rulers B and C swing around axes at P, Q, and R, and axes Q and R should be snug-fitting yet slide freely up and down in the slot cut in the triangle. The length $\overline{PR}$ is an arbitrary, fixed length a. The length $\overline{PQ}$ is adjustable; it should be set so that

$$PQ = a\frac{V_2}{V_1} \tag{1}$$

where V_1 and V_2 are the seismic velocities in the respective media.

Stick pins at points G and S and place the device on the paper so the lower edge of C touches the pin at G and the upper edge of B touches the pin at S. The

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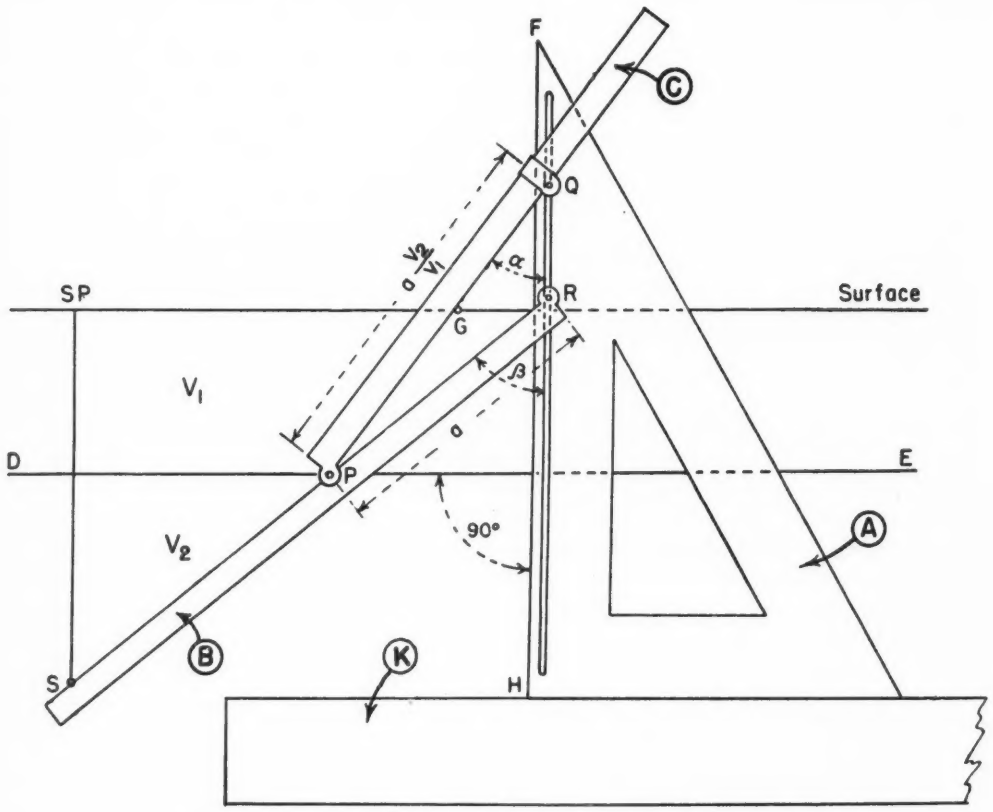

FIG. 2. Graphical device for determining minimum travel-time path across single interface.

triangle should rest on a steel ruler K parallel to the interface DE. Keeping the rulers constantly in touch with the pins at S and G, move the triangle along the steel ruler to the right or left until you can bring point P on line DE. Then draw the lines PS and PG which furnish the solution of the problem. If higher accuracy is needed, this graphical solution could be used as a first approximation in the trial-and-error method.

The mathematical proof is very simple. It is stated that at any position of the rulers B and C (see Figure 2)

$$\sin \alpha / \sin \beta = V_1/V_2. \tag{2}$$

Considering the sketch in Figure 3,

$$\sin \alpha / \sin \beta = \frac{p/\overline{PQ}}{p/\overline{PR}} = \overline{PR}/\overline{PQ}. \tag{3}$$

It can be seen that p is eliminated in equation (3); that is, this equation is valid regardless of the position of P on line DE.

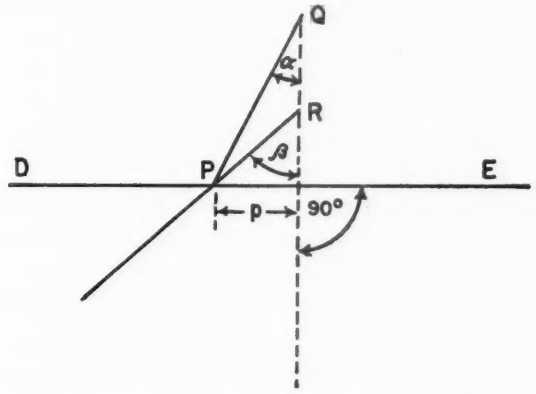

FIG. 3. Geometrical representation of device shown in Figure 2.

Let $\overline{PR}=a$, and $\overline{PQ}=a(V_2/V_1)$, then

$$\sin \alpha/\sin \beta = a/(aV_2/V_1) = V_1/V_2, \text{ q.e.d.} \tag{4}$$

If P is moved to the right to fall on line QR, then PQ and PR coincide with line QR. That is, the ray normal to the interface is not refracted. If R falls on line DE, then $\beta=90°$, and

$$\sin \alpha = \overline{PR}/\overline{PQ} = a/(aV_2/V_1) = V_1/V_2 \tag{5}$$

and α is the critical angle.

Ruler C (Figure 2) should carry a scale of aV_2/V_1 for values greater than a, and the position of Q should be adjustable to fit any V_2/V_1.

Naturally, with this device it is easy to find the refracted ray if the incident ray to an interface is given and V_1 and V_2 are known. Adjust Q so $\overline{PQ}=aV_2/V_1$.

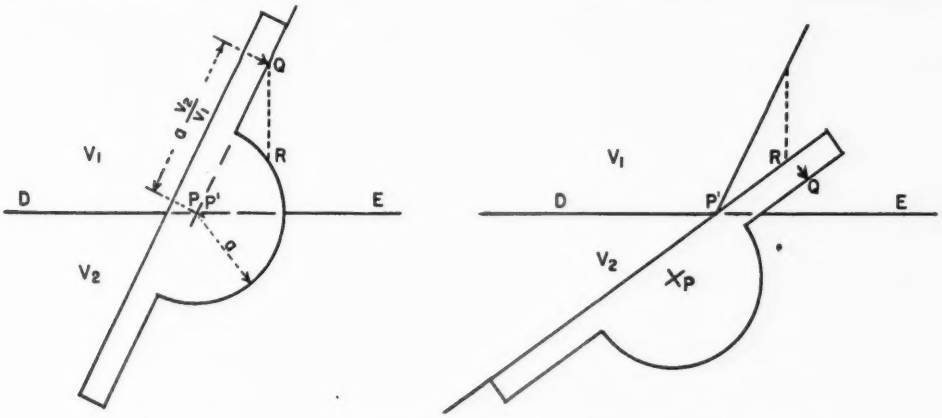

FIG. 4. Use of second graphical device for determining path of refracted ray when ray incident at interface is known.

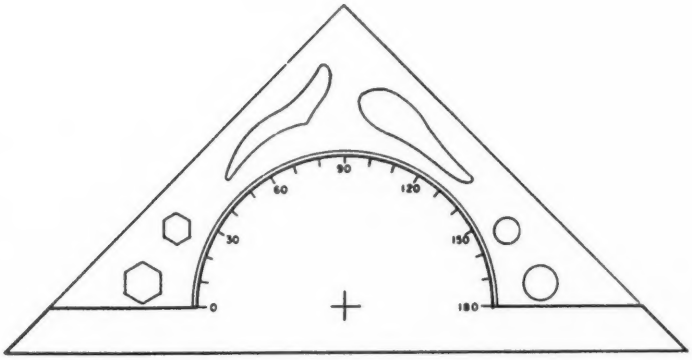

FIG. 5. Protractor-triangle from which device shown in Figure 4 can be cut.

Place the device on the paper so the lower edge of C coincides with the incident ray and point P is on the interface DE (Figure 2). Turning the FH edge of the triangle into a position normal to the interface DE, ruler B will give the direction of the refracted ray.

This second problem can be solved by a much simpler device, shown in Figure 4, which can be cut out from any protractor-triangle as shown in Figure 5.

Draw the interface DE and the incident ray. Mark Q so that $\overline{PQ}=aV_2/V_1$ and place the device so P coincides with P', the intersection of the incident ray and the interface DE; furthermore, PQ coincides with the incident ray. Then drop a line from Q normal to DE until it intersects the half circle at R. Mark this point on the paper and connect R with P' as shown on the right hand side of Figure 4. The extension of this line below DE is the refracted ray. Working on tracing paper it is convenient to place cross section paper under the tracing paper so its lines are parallel and normal to DE. Then the projection of Q to the semi-

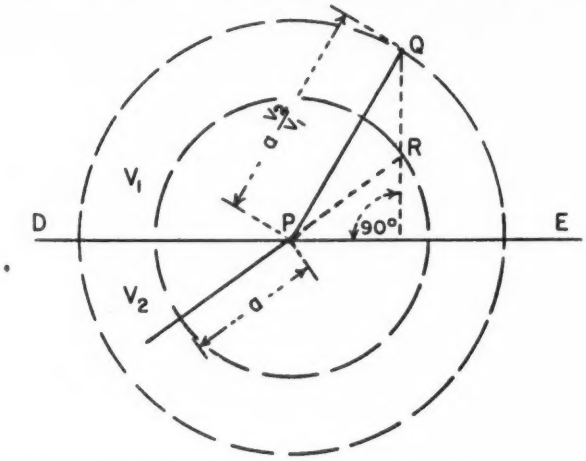

FIG. 6. Geometric solution for refracted ray when incident ray to interface is known.

circle can be easily made by following the lines of the cross-section paper. If the work is done on cross-section paper and *DE* is not parallel to the mesh lines, place another cross-section paper of different color (and preferably of different mesh) under the cross-section paper in such a manner that its lines are parallel and normal to *DE*. Then the projection of *Q* to the semicircle can be made without difficulty.

The first problem discussed above can be solved with this device also by trial and error. The mathematical proof is identical with that given above for the first device. (See equations (4) and (5), and Figure 3.)

Finally, the refracted ray can be constructed geometrically by the following procedure.

In Figure 6, let *DE* again be the interface between two media with seismic velocities V_1 and V_2, and *PQ* the incident ray. Draw a circle with an arbitrary radius a around *P* as center and a concentric circle with radius aV_2/V_1. Since *QR* is normal to *DE*, *RP* gives the direction of the refracted ray.

DETERMINATION OF DIPS AND DEPTHS OF GEOLOGICAL LAYERS BY THE SEISMIC REFRACTION METHOD*

LINDONOR MOTA†

ABSTRACT

Equations are developed for computing depths and dips of 1, 2, 3, · · · , n inclined interfaces from seismic refraction data without the aid of graphical techniques.

INTRODUCTION

In this paper mathematical expressions are developed for seismic refractions from a number of homogeneous velocity layers having plane dipping interfaces. A computing procedure is described which utilizes these expressions to determine depth and dip of each refractor.[1]

It is assumed that the seismic energy is recorded at closely spaced intervals on the surface along a line which includes the source point. This control line extends far enough out from the shot to insure penetration of refracted waves into the nth layer. At the far end another shotpoint is used for recording from the opposite direction at each geophone station. These data are displayed on time-distance graphs to facilitate identification of intercept times and slopes from which depths and dips of the refracting layers are obtainable.

ASSUMPTIONS

The following statements describe the assumptions involved:

1. All necessary corrections have been applied to the times used in the construction of the time-distance graphs.

2. The plane used for calculation is the refraction plane common to the n refractors, so that Fermat's principle in general and Snell's law in particular can be applied within this plane. This is theoretically correct only if the layers are all oriented normal to the refraction profile under consideration. However, if the true dips of the refractors are small, it is admissible in practice to apply this assumption even without common orientation of the layers.

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[1] When he submitted this paper, Mr. Mota was not cognizant of the publication of Ewing, Woollard, and Vine (1939) in which equations were developed for solving the problem stated here. The derivation given by Mota is somewhat different and the final results are presented in a more detailed and explicit form for the n-layer case. Many geophysicists, particularly those working in field offices, may have difficulty in getting access to the 1939 paper. For these reasons, it has been considered desirable to publish this paper in spite of the prior publication on the same subject.—*The Editor.*

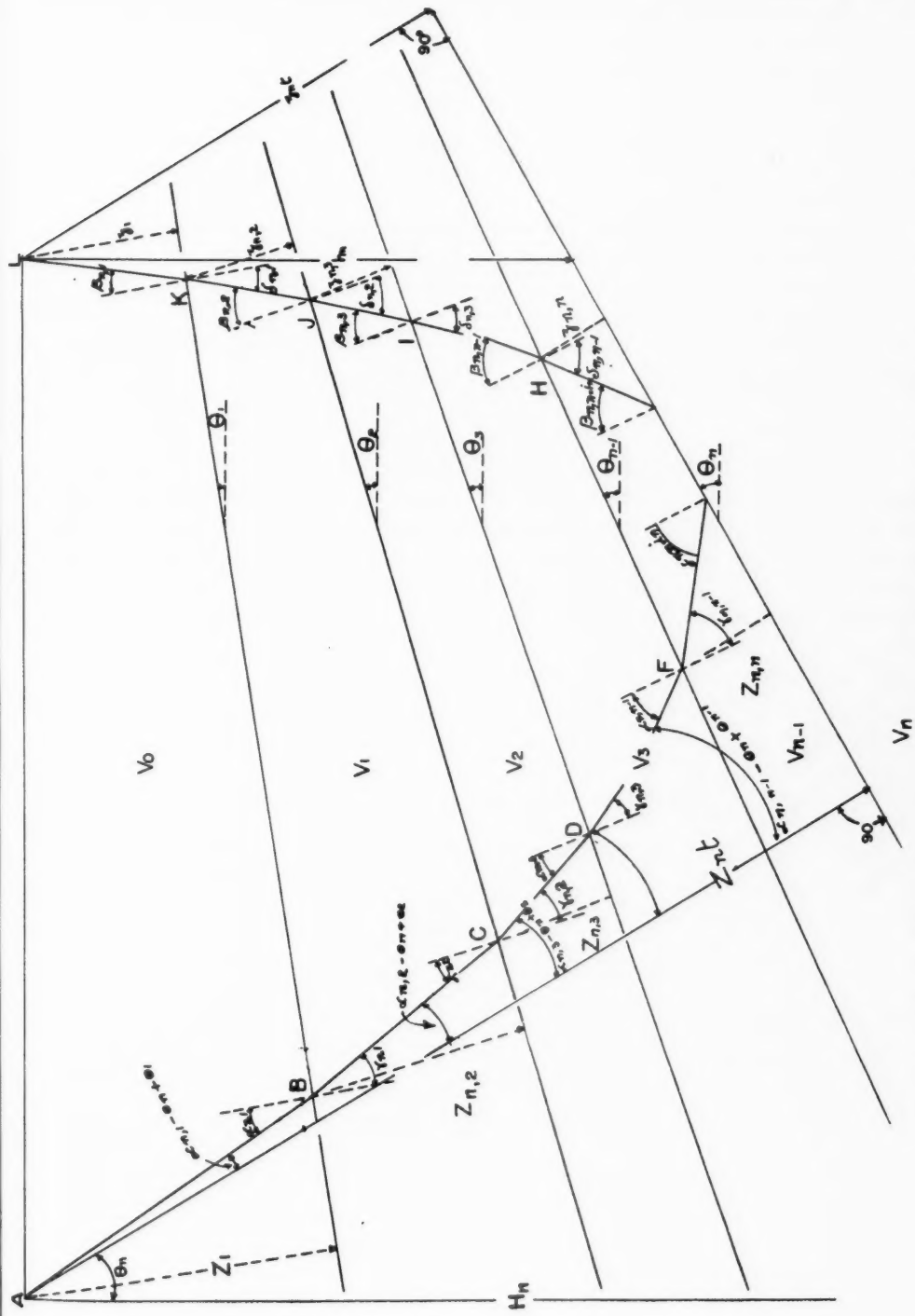

FIG. 1. Refraction along the top of a layer with velocity V_n overlain by n layers with successively lower velocities $V_{n-1}, \cdots V_3, V_2, V_1$, and V_0.

3. Angles from the horizontal upward and to the left are taken as positive; those upward and to the right, as negative.

4. The true velocities V_0, V_1, V_2, $\cdots$ V_n of the longitudinal wave propagation within the 1st, 2nd, 3rd, $\cdots$, $(n+1)$st layers, respectively, in whatever direction taken, are constant. (Each successively deeper layer is assumed to have a higher velocity than that of any shallower layer so that a refraction can be obtained from it.)

The apparent high and low velocities observed in opposite directions from the shotpoint are called V_{1a}, V_{2a}, V_{3a}, $\cdots$, V_{na} and V_{1b}, V_{2b}, V_{3b}, $\cdots$, V_{nb} for the respective layers.

5. The refractor along which the energy is supposed to travel and return to the surface via the critical angle is considered plane and continuous from one end of the profile to the other.

GENERAL RELATIONSHIPS

Figure 1 illustrates the geometry and ray paths for the most general case of n layers. The thickness of the kth layer at the point where the ray refracted along the nth layer (at the bottom of its path) penetrates its top is designated by $Z_{n,k}$ on the downdip side of the trajectory and by $z_{n,k}$ on the updip side. The angle of dip of the nth interface is θ_n. The angles made by the ray refracted along the nth layer with the normal to the kth interface on the downdip side of the trajectory are $\alpha_{n,k}$ above the interface and $\gamma_{n,k}$ below it. The corresponding angles on the updip side are $\beta_{n,k}$ and $\delta_{n,k}$. The total depth (vertical) to the nth interface below the surface at the downdip end (A) of the trajectory is H_n; below the updip end (L) it is h_n. The perpendicular distance from A to the nth refractor is Z_{nt}; from L it is z_{nt}.

With the assumptions in the preceding section, Figure 1 gives:

$$\left.\begin{aligned} &\left.\begin{aligned} \alpha_{n,2} &= \gamma_{n,1} - \theta_2 + \theta_1 \\ \beta_{n,2} &= \delta_{n,1} + \theta_2 - \theta_1 \end{aligned}\right\} \\ &\quad \cdots\cdots\cdots\cdots \\ &\left.\begin{aligned} \alpha_{n,n} &= \gamma_{n,n-1} - \theta_n + \theta_{n-1} \\ \beta_{n,n} &= \delta_{n,n-1} + \theta_n - \theta_{n-1}. \end{aligned}\right\} \end{aligned}\right\} \tag{1}$$

From this we see

$$\left.\begin{aligned} \theta_n &= \frac{\gamma_{n,n-1} - \delta_{n,n-1}}{2} + \theta_{n-1} \\ i_n &= \frac{\gamma_{n,n-1} + \delta_{n,n-1}}{2}, \end{aligned}\right\} \tag{2}$$

considering that $\alpha_{n,n} = \beta_{n,n} = i_n$.

Snell's Law applies as follows:

$$\left.\begin{aligned}
\frac{\sin \alpha_{n,1}}{\sin \gamma_{n,1}} = \frac{\sin \beta_{n,1}}{\sin \delta_{n,1}} = \sin i_1 = \frac{V_0}{V_1} \\
\frac{\sin \alpha_{n,2}}{\sin \gamma_{n,2}} = \frac{\sin \beta_{n,2}}{\sin \delta_{n,2}} = \sin i_2 = \frac{V_1}{V_2} \\
\frac{\sin \alpha_{n,n-1}}{\sin \gamma_{n,n-1}} = \frac{\sin \beta_{n,n-1}}{\sin \delta_{n,n-1}} = \sin i_{n-1} = \frac{V_{n-2}}{V_{n-1}}.
\end{aligned}\right\} \tag{3}$$

In particular

$$\sin \alpha_{n,n} = \sin \beta_{n,n} = \sin i_n = \frac{V_{n-1}}{V_n}, \quad \text{because} \quad \gamma_{n,n} = \delta_{n,n} = 90°. \tag{4}$$

The depth of the refractor beneath end points of the refraction profile is given by

$$\left.\begin{aligned}
H_n &= \frac{1}{\cos \theta_n} \cdot Z_{nt} \\
&= \frac{1}{\cos \theta_n}\left[\frac{Z_{n,1} \cos (\alpha_{n,1} - \theta_n + \theta_1)}{\cos \alpha_{n,1}} + \frac{Z_{n,2} \cos (\alpha_{n,2} - \theta_n + \theta_2)}{\cos \alpha_{n,2}} + \cdots \right. \\
&\quad \left. + \frac{Z_{n,n-1} \cos (\alpha_{n,n-1} - \theta_n + \theta_{n-1})}{\cos \alpha_{n,n-1}} + Z_{n,n}\right] \\
h_n &= \frac{1}{\cos \theta_n} \cdot z_{nt} \\
&= \frac{1}{\cos \theta_n}\left[\frac{z_{n,1} \cos (\beta_{n,1} + \theta_n - \theta_1)}{\cos \beta_{n,1}} + \frac{z_{n,2} \cos (\beta_{n,2} + \theta_n - \theta_2)}{\cos \beta_{n,2}} + \cdots \right. \\
&\quad \left. + \frac{z_{n,n-1} \cos (\beta_{n,n-1} + \theta_n - \theta_{n-1})}{\cos \beta_{n,n-1}} + z_{n,n}\right].
\end{aligned}\right\} \tag{5}$$

Thickness of the mth layer measured where a ray crosses en route to the nth refractor is related to thickness of this layer measured where a ray crosses en route to the $(n-1)$th refractor by the following expression:

$$\left.\begin{aligned}
Z_{n,m} = Z_{n-1,m} + \{&Z_1(\tan \alpha_{n-1,1} - \tan \alpha_{n,1}) \\
&\cdot [\cos (\theta_2 - \theta_1) \cos (\theta_3 - \theta_2) \cdots \cos (\theta_{m-1} - \theta_{m-2})] \\
&+ (Z_{n-1,2} \tan \alpha_{n-1,2} - Z_{n,2} \tan \alpha_{n,2}) \\
&\cdot [\cos (\theta_3 - \theta_2) \cos (\theta_4 - \theta_3) \cdots \cos (\theta_{m-1} - \theta_{m-2})] \\
+ \cdots + (Z_{n-1,m-1} \tan \alpha_{n-1,m-1} &- Z_{n,m-1} \tan \alpha_{n,m-1})\} \sin (\theta_m - \theta_{m-1}).
\end{aligned}\right\} \tag{6}$$

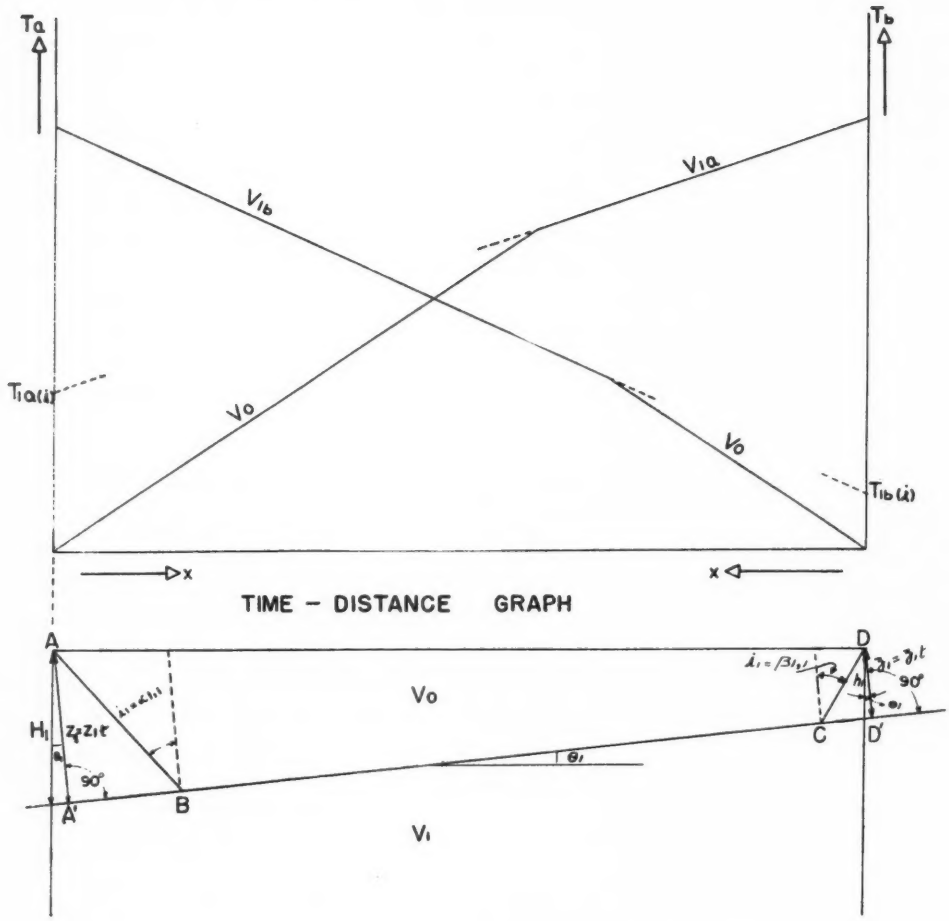

FIG. 2. Refraction along the top of a layer with velocity V_1 overlain by a layer with a lower velocity V_0.

CASE OF A SINGLE REFRACTOR

From Figure 2 we obtain:

$$\left.\begin{aligned} T_{1a} &= \frac{x}{V_0}\sin(\beta_{1,1} - \theta_1) + \frac{Z_1}{V_0}\cdot 2\cos i_1 \equiv \text{Travel time up dip.} \\ T_{1b} &= \frac{x}{V_0}\sin(\alpha_{1,1} + \theta_1) + \frac{z_1}{V_0}\cdot 2\cos i_1 \equiv \text{Travel time down dip.} \end{aligned}\right\} \tag{7}$$

Derivatives of these expressions yield

$$\frac{dx}{dT_{1b}} = \frac{V_0}{\sin(\alpha_{1,1} + \theta)} = V_{1b} \tag{8}$$

and

$$\frac{dx}{dT_{1a}} = \frac{V_0}{\sin(\beta_{1,1} - \theta_1)} = V_{1a}. \tag{9}$$

V_{1a} and V_{1b} are given by the T-X graph of Figure 2.

The angle of incidence into the refracting bed, i_1, the angle of dip of the refractor, θ_1, and true velocity V_1 are given by

$$\left.\begin{aligned} i_1 &= \alpha_{1,1} = \beta_{1,1} = \frac{1}{2}\left[\arcsin\frac{V_0}{V_{1a}} + \arcsin\frac{V_0}{V_{1b}}\right] \\ \theta_1 &= \frac{1}{2}\left[\arcsin\frac{V_0}{V_{1b}} - \arcsin\frac{V_0}{V_{1a}}\right] \\ V_1 &= \frac{V_0}{\sin i_1}. \end{aligned}\right\} \tag{10}$$

For $x=0$, $T_{1a}=T_{1a(i)}$ and $T_{1b}=T_{1b(i)}$. These are the intercept times. Equation (7) gives us

$$\left.\begin{aligned} Z_1 &= \frac{V_0 T_{1a(i)}}{2\cos i_1} \\ z_1 &= \frac{V_0 T_{1b(i)}}{2\cos i_1} \end{aligned}\right\} \tag{11}$$

for layer thickness and

$$\left.\begin{aligned} H_1 &= \frac{Z_{1t}}{\cos\theta_1} \\ h_1 &= \frac{z_{1t}}{\cos\theta_1} \end{aligned}\right\} \tag{12}$$

for depth.

CASE OF TWO REFRACTORS

By following the same line of reasoning, we can see from Figure 3 that:

$$\left.\begin{aligned} T_{2a} &= \frac{x}{V_0}\sin(\beta_{2,1} - \theta_1) + \frac{Z_1}{V_0}\cdot\frac{\cos(\alpha_{2,1} + \beta_{2,1}) + 1}{\cos\alpha_{2,1}} + \frac{Z_{2,2}}{V_1}\cdot 2\cos i_2 \\ T_{2b} &= \frac{x}{V_0}\sin(\alpha_{2,1} + \theta_1) + \frac{z_1}{V_0}\cdot\frac{\cos(\alpha_{2,1} + \beta_{2,1}) + 1}{\cos\beta_{2,1}} + \frac{z_{2,2}}{V_1}\cdot 2\cos i_2 \end{aligned}\right\} \tag{13}$$

$$\left.\begin{aligned} \frac{dx}{dT_{2a}} &= \frac{V_0}{\sin(\beta_{2,1} - \theta_1)} = V_{2a} \\ \frac{dx}{dT_{2b}} &= \frac{V_0}{\sin(\alpha_{2,1} + \theta_1)} = V_{2b} \end{aligned}\right\} \tag{14}$$

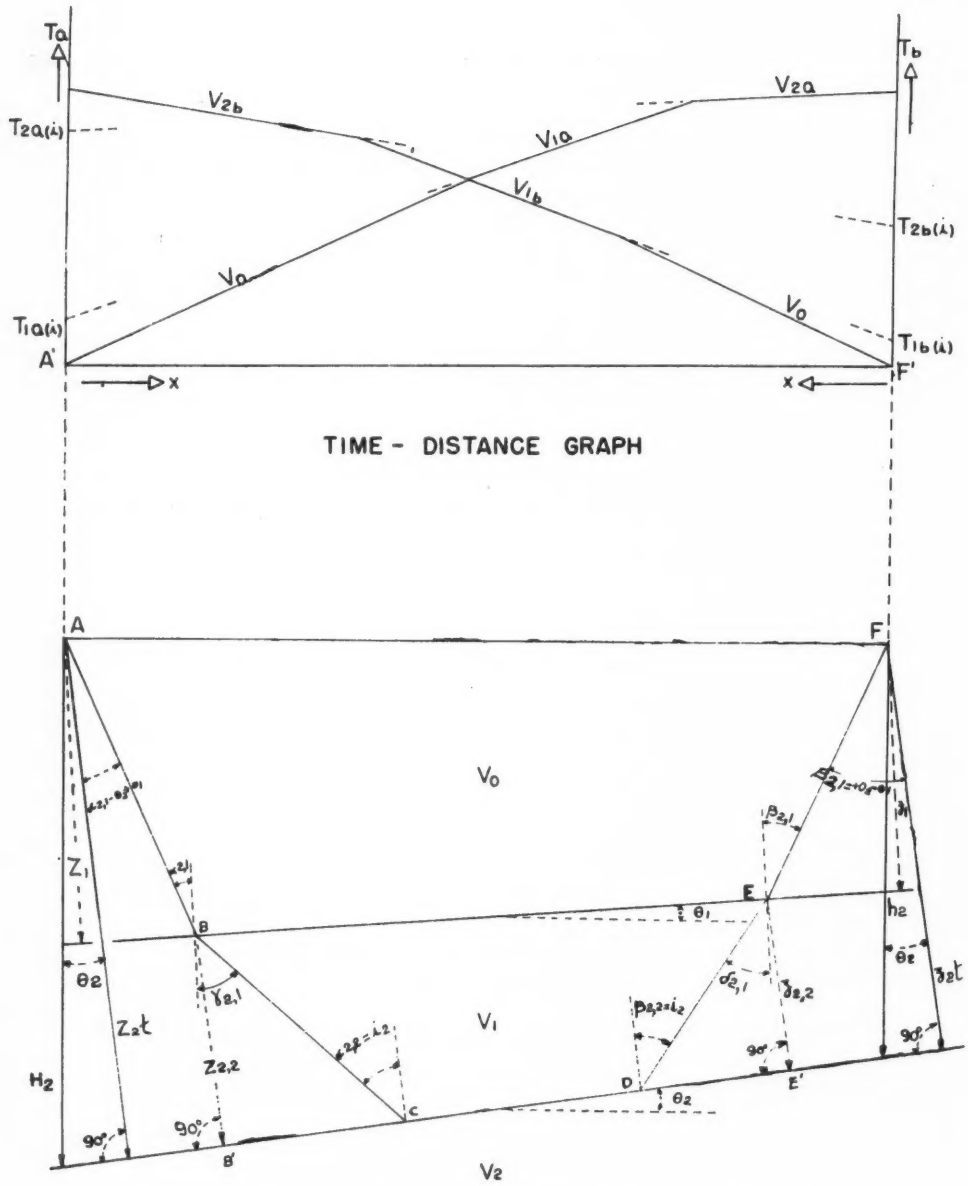

FIG. 3. Refraction along the top of a layer with velocity V_2 overlain by two layers with successively lower velocities, V_1 and V_0.

$$\left.\begin{aligned}\gamma_{2,1} &= \arcsin\left(\frac{V_1}{V_0}\sin\alpha_{2,1}\right)\\ \delta_{2,1} &= \arcsin\left(\frac{V_1}{V_0}\sin\beta_{2,1}\right).\end{aligned}\right\} \tag{15}$$

$$\left.\begin{aligned} i_2 &= \alpha_{2,2} = \beta_{2,2} = \frac{\gamma_{2,1}+\delta_{2,1}}{2} \equiv \text{critical angle}\\ \theta_2 &= \frac{\gamma_{2,1}-\delta_{2,1}}{2} + \theta_1 \equiv \text{dip}\\ V_2 &= \frac{V_1}{\sin i_2} \equiv \text{true velocity.}\end{aligned}\right\} \tag{16}$$

$$\left.\begin{aligned} Z_{2,2} &= \frac{V_1\left(T_{2a(i)} - \frac{Z_1}{V_0}\cdot\frac{\cos(\alpha_{2,1}+\beta_{2,1})+1}{\cos\alpha_{2,1}}\right)}{2\cos i_2}\\ z_{2,2} &= \frac{V_1\left(T_{2b(i)} - \frac{z_1}{V_0}\cdot\frac{\cos(\alpha_{2,1}+\beta_{2,1})+1}{\cos\beta_{2,1}}\right)}{2\cos i_2}.\end{aligned}\right\} \tag{17}$$

$$\left.\begin{aligned} H_2 &= \frac{Z_{2t}}{\cos\theta_2} = \frac{1}{\cos\theta_2}\left[Z_1\frac{\cos(\alpha_{2,1}-\theta_2+\theta_1)}{\cos\alpha_{2,1}} + Z_{2,2}\right]\\ h_2 &= \frac{z_{2t}}{\cos\theta_2} = \frac{1}{\cos\theta_2}\left[z_1\frac{\cos(\beta_{2,1}+\theta_2-\theta_1)}{\cos\beta_{2,1}} + z_{2,2}\right].\end{aligned}\right\} \tag{18}$$

CASE OF THREE REFRACTORS

Upon extending this reasoning to include three refractors as in Figure 4 we have:

$$\left.\begin{aligned} T_{3a} &= \frac{x}{V_0}\sin(\beta_{3,1}-\theta_1) + \frac{Z_1}{V_0}\cdot\frac{\cos(\alpha_{3,1}+\beta_{3,1})+1}{\cos\alpha_{3,1}} + \frac{Z_{3,2}}{V_1}\cdot\frac{\cos(\alpha_{3,2}+\beta_{3,2})+1}{\cos\alpha_{3,2}}\\ &\quad + \frac{Z_{3,3}}{V_2}\cdot 2\cos i_3\\ T_{3b} &= \frac{x}{V_0}\sin(\alpha_{3,1}+\theta_1) + \frac{z_1}{V_0}\cdot\frac{\cos(\alpha_{3,1}+\beta_{3,1})+1}{\cos\beta_{3,1}} + \frac{z_{3,2}}{V_1}\cdot\frac{\cos(\alpha_{3,2}+\beta_{3,2})+1}{\cos\beta_{3,2}}\\ &\quad + \frac{z_{3,3}}{V_2}\cdot 2\cos i_3.\end{aligned}\right\} \tag{19}$$

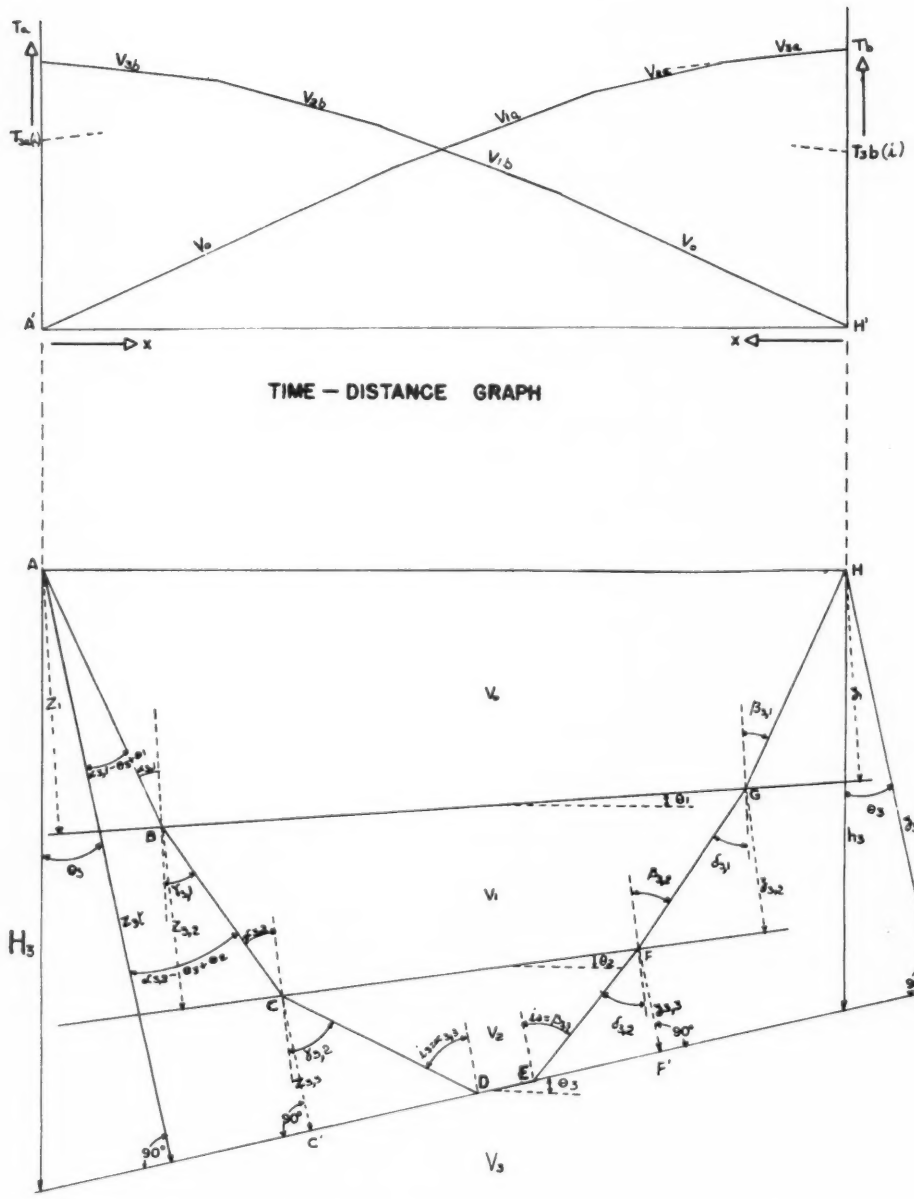

FIG. 4. Refraction along the top of a layer with velocity V_3 overlain by three layers with successively lower velocities, V_2, V_1, V_0.

$$\left.\begin{aligned} i_3 &= \alpha_{3,3} = \beta_{3,3} = \frac{\gamma_{3,2}+\delta_{3,2}}{2} \equiv \text{critical angle} \\ \theta_3 &= \frac{\gamma_{3,2}-\delta_{3,2}}{2} + \theta_2 \equiv \text{dip} \\ V_3 &= \frac{V_2}{\sin i_3} \equiv \text{true velocity.} \end{aligned}\right\} \tag{20}$$

$$\left.\begin{aligned} Z_{3,3} &= \frac{V_2\left[T_{3a(i)} - \frac{Z_1}{V_0}\cdot\frac{\cos(\alpha_{3,1}+\beta_{3,1})+1}{\cos\alpha_{3,1}} - \frac{Z_{3,2}}{V_1}\cdot\frac{\cos(\alpha_{3,2}+\beta_{3,2})+1}{\cos\alpha_{3,2}}\right]}{2\cos i_3} \\ z_{3,3} &= \frac{V_2\left[T_{3b(i)} - \frac{z_1}{V_0}\cdot\frac{\cos(\alpha_{3,1}+\beta_{3,1})+1}{\cos\beta_{3,1}} - \frac{z_{3,2}}{V_1}\cdot\frac{\cos(\alpha_{3,2}+\beta_{3,2})+1}{\cos\beta_{3,2}}\right]}{2\cos i_3}. \end{aligned}\right\} \tag{21}$$

$$\left.\begin{aligned} H_3 &= \frac{Z_{3t}}{\cos\theta_3} \\ &= \frac{1}{\cos\theta_3}\left[\frac{Z_1\cos(\alpha_{3,1}-\theta_3+\theta_1)}{\cos\alpha_{3,1}} + \frac{Z_{3,2}\cos(\alpha_{3,2}-\theta_3+\theta_2)}{\cos\alpha_{3,2}} + Z_{3,3}\right] \\ h_3 &= \frac{z_{3t}}{\cos\theta_3} \\ &= \frac{1}{\cos\theta_3}\left[\frac{z_1\cos(\beta_{3,1}+\theta_3-\theta_1)}{\cos\beta_{3,1}} + \frac{z_{3,2}\cos(\beta_{3,2}+\theta_3-\theta_2)}{\cos\beta_{3,2}} + z_{3,3}\right]. \end{aligned}\right\} \tag{22}$$

CASE OF N REFRACTORS

By induction from the foregoing, one arrives at the following expressions for n refractors (see Figure 1.)

$$\left.\begin{aligned} T_{na} &= \frac{x}{V_0}\cdot\sin(\beta_{n,1}-\theta_1) + \frac{Z_{n,1}}{V_0}\cdot\frac{\cos(\alpha_{n,1}+\beta_{n,1})+1}{\cos\alpha_{n,1}} \\ &\quad + \frac{Z_{n,2}}{V_1}\cdot\frac{\cos(\alpha_{n,2}+\beta_{n,2})+1}{\cos\alpha_{n,2}} + \cdots \\ &\quad + \frac{Z_{n,n-1}}{V_{n-2}}\cdot\frac{\cos(\alpha_{n,n-1}+\beta_{n,n-1})+1}{\cos\alpha_{n,n-1}} + \frac{Z_{n,n}}{V_{n-1}}\cdot 2\cos i_n \\ T_{nb} &= \frac{x}{V_0}\sin(\alpha_{n,1}+\theta_1) + \frac{z_{n,1}}{V_0}\cdot\frac{\cos(\alpha_{n,1}+\beta_{n,1})+1}{\cos\beta_{n,1}} \\ &\quad + \frac{z_{n,2}}{V_1}\cdot\frac{\cos(\alpha_{n,2}+\beta_{n,2})+1}{\cos\beta_{n,2}} + \cdots \\ &\quad + \frac{z_{n,n-1}}{V_{n-2}}\cdot\frac{\cos(\alpha_{n,n-1}+\beta_{n,n-1})+1}{\cos\beta_{n,n-1}} + \frac{z_{n,n}}{V_{n-1}}\cdot 2\cos i_n. \end{aligned}\right\} \tag{23}$$

Derivatives of these equations are simply

$$\frac{dx}{dT_{na}} = \frac{V_0}{\sin(\beta_{n,1} - \theta_1)} = V_{na}$$

and

$$\frac{dx}{dT_{nb}} = \frac{V_0}{\sin(\alpha_{n,1} + \theta_1)} = V_{nb}.$$

Therefore,

$$\beta_{n,1} = \arcsin \frac{V_0}{V_{na}} + \theta_1$$

and

$$\alpha_{n,1} = \arcsin \frac{V_0}{V_{nb}} - \theta_1.$$

$$\left.\begin{aligned} i_n &= \alpha_{n,n} = \beta_{n,n} = \frac{\gamma_{n,n-1} + \delta_{n,n-1}}{2} \equiv \text{critical angle} \\ \theta_n &= \frac{\gamma_{n,n-1} - \delta_{n,n-1}}{2} + \theta_{n-1} \equiv \text{dip} \\ V_n &= \frac{V_{n-1}}{\sin i_n} \equiv \text{true velocity.} \end{aligned}\right\} \tag{24}$$

$$\left.\begin{aligned} Z_{n,n} &= \frac{V_{n-1}\left[T_{na(i)} - \frac{Z_{n,1}}{V_0}\cdot\frac{\cos(\alpha_{n,1}+\beta_{n,1})+1}{\cos\alpha_{n,1}} - \frac{Z_{n,2}}{V_1}\cdot\frac{\cos(\alpha_{n,2}+\beta_{n,2})+1}{\cos\alpha_{n,2}} - \cdots - \frac{Z_{n,n-1}}{V_{n-2}}\cdot\frac{\cos(\alpha_{n,n-1}+\beta_{n,n-1})+1}{\cos\alpha_{n,n-1}}\right]}{2\cos i_n} \\ z_{n,n} &= \frac{V_{n-1}\left[T_{nb(i)} - \frac{z_{n,1}}{V_0}\cdot\frac{\cos(\alpha_{n,1}+\beta_{n,1})+1}{\cos\beta_{n,1}} - \frac{z_{n,2}}{V_1}\cdot\frac{\cos(\alpha_{n,2}+\beta_{n,2})+1}{\cos\beta_{n,2}} - \cdots - \frac{z_{n,n-1}}{V_{n-2}}\cdot\frac{\cos(\alpha_{n,n-1}+\beta_{n,n-1})+1}{\cos\beta_{n,n-1}}\right]}{2\cos i_n}. \end{aligned}\right\} \tag{25}$$

$$\left.\begin{aligned} H_n &= \frac{Z_{nt}}{\cos\theta_n} = \frac{1}{\cos\theta_n}\left[\frac{Z_{n,1}\cos(\alpha_{n,1}-\theta_n+\theta_1)}{\cos\alpha_{n,1}} + \frac{Z_{n,2}\cos(\alpha_{n,2}-\theta_n+\theta_2)}{\cos\alpha_{n,2}}\right. \\ &\qquad \left. + \cdots + \frac{Z_{n,n-1}\cos(\alpha_{n,n-1}-\theta_n+\theta_{n-1})}{\cos\alpha_{n,n-1}} + Z_{n,n}\right] \\ h_n &= \frac{z_{nt}}{\cos\theta_n} = \frac{1}{\cos\theta_n}\left[\frac{z_{n,1}\cos(\beta_{n,1}+\theta_n-\theta_1)}{\cos\beta_{n,1}} + \frac{z_{n,2}\cos(\beta_{n,2}+\theta_n-\theta_2)}{\cos\beta_{n,2}}\right. \\ &\qquad \left. + \cdots + \frac{z_{n,n-1}\cos(\beta_{n,n-1}+\theta_n-\theta_{n-1})}{\cos\beta_{n,n-1}} + z_{n,n}\right]. \end{aligned}\right\} \quad (26)$$

Incidentally, if all refracting interfaces are horizontal, these expressions assume the well known forms listed below:

$$T_{na} = T_{nb} = T_n = \frac{x}{V_0}\sin\alpha_{n,1} + \frac{Z_{n,1}}{V_0}\cdot 2\cos\alpha_{n,1} + \frac{Z_{n,2}}{V_1}\cdot 2\cos\alpha_{n,2} + \frac{Z_{n,3}}{V_2}\cdot 2\cos\alpha_{n,3} + \cdots + \frac{Z_{n,n}}{V_{n-1}}\cdot 2\cos i_n; \quad (27)$$

$$Z_{n,n} = z_{n,n} = \frac{V_{n-1}\left[\frac{T_{n(i)}}{2} - \frac{Z_{n,1}}{V_0}\cos\alpha_{n,1} - \frac{Z_{n,2}}{V_1}\cos\alpha_{n,2} - \frac{Z_{n,3}}{V_2}\cos\alpha_{n,3} - \cdots - \frac{Z_{n,n-1}}{V_{n-2}}\cos\alpha_{n,n-1}\right]}{\cos i_n}; \quad (28)$$

$$H_n = h_n = Z_{n,1} + Z_{n,2} + Z_{n,3} + \cdots + Z_{n,n} \equiv \text{depth}. \quad (29)$$

STEPS OF CALCULATION FOR THE nth REFRACTOR

The following quantities are available on the time-distance graph or are computed from refractions which penetrated only into shallower beds:

$\theta_1, \theta_2, \theta_3 \cdots \theta_{n-1}$;

$Z_1; Z_{n-1,2}; Z_{n-1,3} \cdots Z_{n-1,n-1}$; or

$z_1; z_{n-1,2}; z_{n-1,3} \cdots z_{n-1,n-1}$

$\alpha_{n-1,1}, \alpha_{n-1,2}; \alpha_{n-1,3} \cdots \alpha_{n-1,n-1}$; or

$\beta_{n-1,1}, \beta_{n-1,2}\ \beta_{n-1,3} \cdots \beta_{n-1,n-1}$;

V_{na};

V_{nb}.

The quantities one desires to obtain with a refraction which penetrates into the $(n+1)$th layer are θ_n and H_n or h_n.

The angles $\alpha_{n,1}$ and $\beta_{n,1}$ are obtained from the arcsin relationships involving the apparent velocities V_{na} and V_{nb}. By substitution of $\alpha_{n,1}$ and $\beta_{n,1}$ into equation (3) we obtain $\gamma_{n,1}$ and $\delta_{n,1}$. With these values, $\alpha_{n,2}$ and $\beta_{n,2}$ can be calculated from equation (1). Again from equation (3) we calculate $\gamma_{n,2}$ and $\delta_{n,2}$ and so successively to $\gamma_{n,n-1}$ and $\delta_{n,n-1}$, from which angle θ_n and the critical angle $i_n=\alpha_{n,n}$ are obtained by means of equation (2). In this manner the angle θ_n, the first unknown of the problem, is determined.

With $\alpha_{n,1}$; $\alpha_{n,2} \cdots \alpha_{n,n}$, and $\beta_{n,1}$; $\beta_{n,2} \cdots \beta_{n,n}$, and by means of equation (6), we calculate, $Z_{n,2}$; $Z_{n,2} \cdots Z_{n,n-1}$ or $z_{n,2}$; $z_{n,3} \cdots z_{n,n-1}$.

After this we calculate $Z_{n,n-2}$, or $z_{n,n-2}$, using equation (25) and finally H_n or h_n, by means of equation (26), determining in this manner the depth, which constitutes the second unknown of the problem.

Finally V_n can be calculated, using equation (4).

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LEAST SQUARES POLYNOMIAL FITTING TO GRAVITATIONAL DATA AND DENSITY PLOTTING BY DIGITAL COMPUTERS*

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ABSTRACT

The fitting of a nth order polynomial in x and y to gravity data by least squares is discussed. A consideration of the normal equations for the general case shows certain simplifications resulting from rectangularity in data distribution. Some sample residual maps are constructed. Density plotting, made possible by the digital computer, is described and illustrated. It is shown that this process can serve as a substitute for contouring when only a qualitative picture is desired.

INTRODUCTION

There is some question whether or not the removal of regional effects from gravity may be effectively accomplished by the method of least squares. One of the basic assumptions in its application is that the regional be a relatively low order effect. By this is meant that, over the area analyzed, the true regional could be well approximated by a low order polynomial while other anomalies could not. In gravity work this is almost by definition a justified assumption. Agocs (1951) sets up an artificial example in which this is the case. He uses a plane surface, or first order polynomial, for the fitting, and demonstrates how the residual anomaly is better determined by least squares than by the use of the "arithmetic mean regional" procedure. Perhaps the strongest argument in favor of least squares residuals as opposed to methods in which the regional is estimated locally (by integration or summation of Bouguer gravity in a neighborhood of the point considered) is that the user has a tight control on the order of the approximating function. High local anomalies or blunders in observation must give locally unrealistic estimates of the regional from local summation methods. It may be argued that these very anomalies are weighted by their squares in the least squares method, thereby causing undue effects in the overall picture. However, if a reasonably large number of data points is considered, the actual effect is a slight shifting or warping of the polynomial surface, without materially affecting the relative residual contours. In any event, for the purposes of this paper it is assumed that the method deserves further study.

For practical application it is desirable to use polynomials of various orders. Computation and data handling become a serious problem as the polynomial order increases, which probably tends to hinder experimentation with the least squares method. It is the principal aim of this paper to discuss the use of poly-

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nomials of general order and the possibilities of reducing the computational problem. In addition the author wishes to present a possible alternative to contour mapping as a means of examining residuals. This new method, made possible by the high speed digital computer, has very general application to contouring problems. Special applications of the technique to other geophysical data reduction problems are being investigated at MIT.

THE NORMAL EQUATIONS

Gravity values $g(xy)$ are given at discrete points over a pattern P in the xy plane, and it is desired to approximate these values by a polynomial such as

$$G(xy) = c_{00} + c_{10}x + c_{01}y,$$

with c_{00}, c_{10}, and c_{01} taking those values which will make

$$I(c_{00}, c_{10}, c_{01}) = \sum_P [g(xy) - G(xy)]^2 = \sum_P R^2(xy)$$

assume a minimum value. $R(xy)$ may then be considered as the gravity value corrected, in this case, for a linear regional trend.

For a polynomial of order n,

$$G(xy) = \sum_{i=0}^{n} \sum_{j=0}^{n-i} c_{ij}x^i y^j, \tag{1}$$

$I(c_{ij}$'s) may be expressed as

$$I(c_{ij}\text{'s}) = \sum_P \left[\sum_{i=0}^{n} \sum_{j=0}^{n-i} \sum_{k=0}^{n} \sum_{l=0}^{n-k} c_{ij}c_{kl}x^{k+i}y^{l+j} \right] - 2\sum_P g(xy) \sum_{i=0}^{n} \sum_{j=0}^{n-i} c_{ij}x^i y^j + \sum_P g^2(xy).$$

To minimize I we differentiate partially with respect to c_{ij} and equate with zero.

$$\frac{\partial I}{\partial c_{ij}} = 2\sum_{k=0}^{n} \sum_{l=0}^{n-k} c_{kl} \sum_P x^{k+i}y^{l+j} - 2\sum_P g x^i y^j = 0$$

or

$$\sum_{k=0}^{n} \sum_{l=0}^{n-k} c_{kl} \sum_P x^{k+i}y^{l+j} = \sum_P g x^i y^j$$

where

$$\begin{aligned} j &= 0, 1, \cdots, (n - i) \\ i &= 0, 1, \cdots, n. \end{aligned} \tag{2}$$

There are the standard normal equations. It is useful to use matrix notation to discuss the properties of this system of equations. In this notation the system becomes:

$$\left[\sum_P x^{k+i}y^{l+j}\right][c_{kl}] = \left[\sum_P gx^iy^j\right]. \tag{3}$$

The formal solution is

$$[c_{kl}] = \left[\sum_P x^{k+i}y^{l+j}\right]^{-1}\left[\sum_P gx^iy^j\right]. \tag{4}$$

DISCUSSION OF THE NORMAL EQUATIONS

The first feature to notice about equation (3) is that the matrix $[\sum x^{k+i}y^{l+j}]$ is a function only of n and P. The inverse matrix therefore does not depend on gravity values and may be found for any polynomial order once the pattern P is given. If the same pattern P is used in various geologic areas the same inverse applies and the solution is obtained by finding the column vector and premultiplying by a known inverse matrix. This is significantly simpler than inverting matrices for each set of data.

It is particularly fortunate that the patterns used in taking gravity data not only are repeated but in addition are frequently rectangular (excluding subsurface studies). Fr. A. Willers (1948, p. 322) demonstrates features resulting

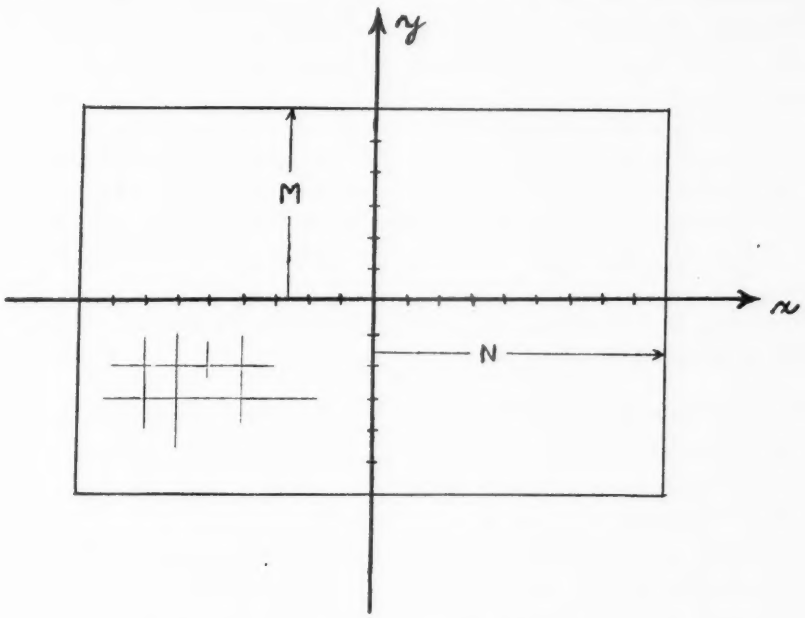

FIG. 1. The rectangular pattern of observations.

from the (normalized) rectangular pattern in the continuous case. In the discrete case axes may be chosen so that the rectangle is symmetrical about them, and ordinates and abscissae taken to be integers as in Figure 1. For this pattern an element of the matrix $[\sum x^{k+i}y^{l+j}]$ becomes

$$\sum_{P} x^{k+i}y^{l+j} = \sum_{\alpha=-N}^{N} \sum_{\beta=-M}^{M} \alpha^{k+i}\beta^{l+j} = \left[\sum_{-N}^{N} \alpha^{k+i}\right]\left[\sum_{-M}^{M} \beta^{l+j}\right]. \tag{5}$$

When either $k+i$ or $l+j$ is odd the corresponding summation vanishes and the element is zero. Only when $k+i$ and $l+j$ are both even is an element non-zero. Now the element $\sum x^{k+i}y^{l+j}$ is the coefficient of c_{kl} in the equation specified by i and j (equation (2)). Divide the c_{kl}'s and the equations into four groups each as follows:

I k odd, l odd	IA i odd, j odd
II k odd, l even	IIA i odd, j even
III k even, l odd	IIIA i even, j odd
IV k even, l even	IVA i even, j even.

All equations in group IA have non-zero coefficients only for c_{kl} in class I since for groups II, III, and IV either $k+i$ or $l+j$ is odd. Similarly group IIA involves only c_{kl} in class II, etc. Furthermore, since $\{kl\}$ and $\{ij\}$ assume the same range of values, there are as many members of a particular equation group as there are members of the corresponding c_{kl} group. In other words, the original system of normal equations has broken down into four independent systems, each sufficient to determine all the c_{kl} in one of the four groups of these unknowns. As might be expected by symmetry, equation groups IIA and IIIA have identical coefficient matrices in the case of a square grid.

The above statements apply to a polynomial of any order. Between polynomials of consequetive order there exists a relationship which may be stated as follows: if the order n of the polynomial is odd (even), all c_{kl} for which $k+l$ is odd (even) will be the same as for the polynomial of order $n+1$. This follows from the fact that, if n is odd the extra c_{kl}'s dealt with in the $(n+1)$th polynomial must all have even $k+l$ so that only equation groups IIA and IIIA are affected. A similar statement holds if n is even.

Summary of Properties of Normal Equations When a Rectangular Grid is Used

1. The normal equations break down into four independent systems corresponding to four classes of coefficients. (Two of these systems have identical coefficient matrices for a square grid.)
2. Specifying the rectangular grid specifies all four inverse matrices regardless of gravity values on the grid.
3. Two of the four systems for an nth order polynomial must be equivalent to two of the four systems for the $(n+1)$th order polynomial.

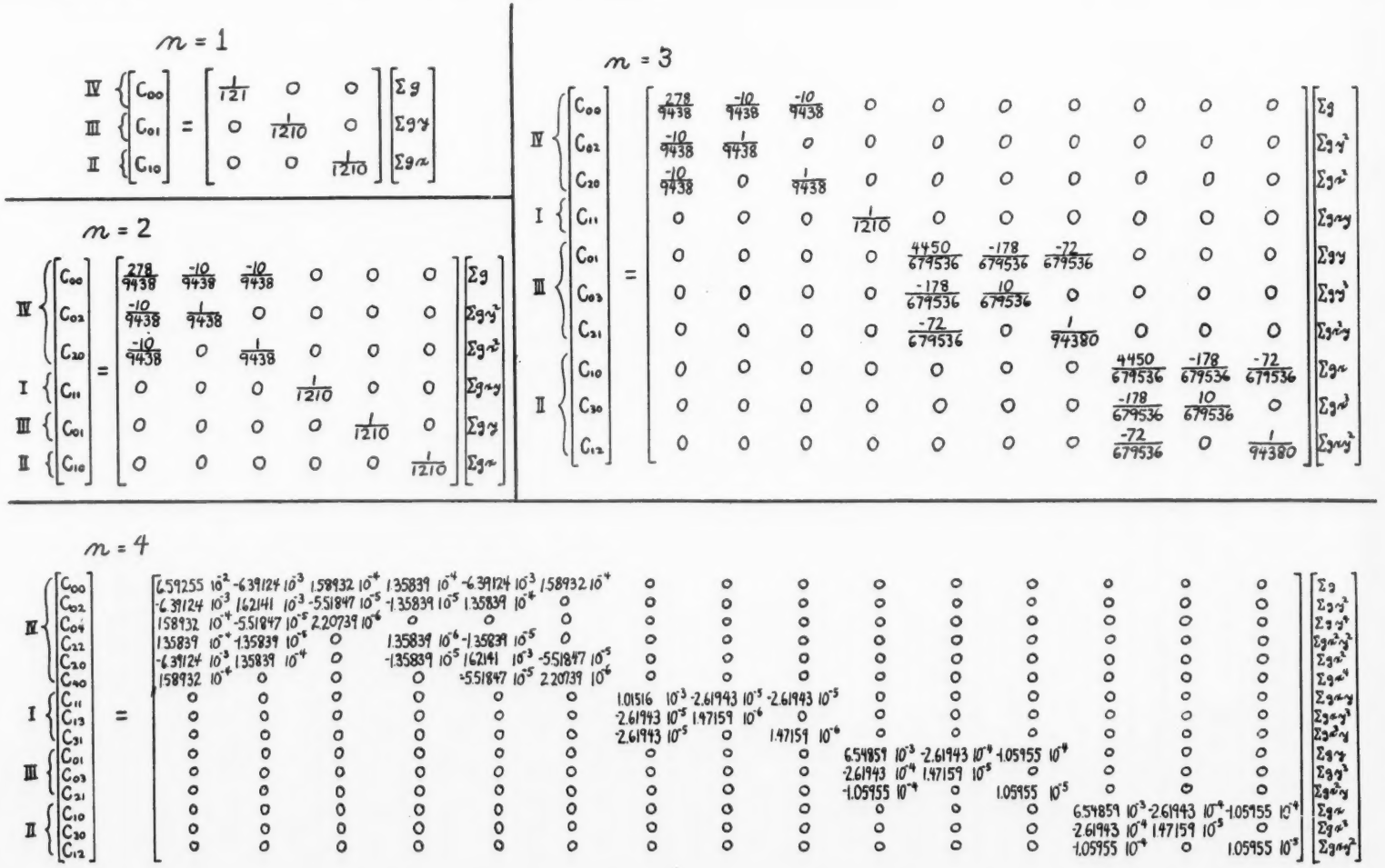

FIG. 2. The solutions in matrix form of the normal equations for various polynomial orders n. Solutions are for a square grid of 121 points.

4. All independent systems have coefficient matrices which are positive definite and symmetric, so that non-singularity is guaranteed.[1]

FORMATION OF THE NORMAL EQUATIONS

The symmetry properties of rectangular grids which reduce normal equations to four separate systems, further simplify the computation of the elements of the coefficient matrix. Limiting the polynomial to order four or less, the relevant elements are

$$\begin{array}{ccccccccc} \sum x^0y^0 & \sum x^2 & \sum x^4 & \sum x^6 & \sum x^8 & \sum y^2 & \sum y^4 & \sum y^6 & \sum y^8 \\ \sum x^2y^2 & \sum x^2y^4 & \sum x^2y^6 & \sum x^4y^2 & \sum x^4y^4 & \sum x^6y^2 & & & \end{array} \tag{6}$$

where the summations are taken over the grid considered.

Referring to Figure 1 it is evident that $\sum x^k$ over the grid equals $\sum x^k$ on a single horizontal line times the number of lines. Thus

$$\sum x^k = (2M + 1) \sum_{\alpha=-N}^{N} \alpha^k,$$

but since k is even

$$\sum x^k = 2(2M + 1) \sum_{\alpha=1}^{N} \alpha^k. \tag{7}$$

Likewise

$$\sum y^l = 2(2N + 1) \sum_{\alpha=1}^{M} \alpha^l. \tag{8}$$

From equation (5)

$$\sum x^k y^l = \left[\sum_{-N}^{N} \alpha^k \right] \left[\sum_{-M}^{M} \beta^l \right] = 4 \left[\sum_{\alpha=1}^{N} \alpha^k \right] \left[\sum_{\beta=1}^{M} \beta^l \right]. \tag{9}$$

Hence the sums (6) are easily derivable from relations (7), (8), and (9) if the quantities $\sum_{\alpha=1}^{N} \alpha^k$ are tabulated. Using this method the elements (6) were computed for six representative grids measuring 10 by 10, 10 by 20, 20 by 20, 30 by 30, 40 by 40, and 50 by 50. They are shown in Table I.

EXAMPLES

From Table I the normal equations were set up for a square grid of 121 points ($N = 5$, $M = 5$). The solutions, in matrix form, to these equations are shown in Figure 2 for polynomials of order 1, 2, 3, and 4. Figure 2 illustrates graphically

[1] The matrix $[\sum xy]$ may be expressed as X^TX, X real, which guarantees symmetry and positive definiteness. The sub-systems may be shown to correspond to principal minors of $[\sum xy]$, for which these properties also hold (Frazer, Duncan, and Collar, 1946, p. 33; Cramer, 1946, p. 115).

TABLE I

$\Sigma x^k y^l$ OVER VARIOUS GRIDS MEASURING $2N \times 2M$
for $k=0, 2, 4, 6, 8$ $l=0, 2 \cdots (8-k)$

	$N=5,\ M=5$	$N=5,\ M=10$	$N=10,\ M=10$	$N=15,\ M=15$	$N=20,\ M=20$	$N=25,\ M=25$
$\Sigma x^0y^0=$	121	231	441	961	1,681	2,601
$\Sigma x^2 =$	1,210	2,310	16,170	76,880	235,340	563,550
$\Sigma x^4 =$	21,538	41,118	1,063,986	11,055,344	59,258,612	219,671,790
$\Sigma x^6 =$	451,330	861,630	83,093,010	1,889,941,040	17,749,376,420	101,885,895,150
$\Sigma x^8 =$	10,185,538	19,445,118	7,044,715,986	351,321,903,344	5,784,339,914,612	51,429,792,671,790
$\Sigma y^2 =$	1,210	8,470	16,170	76,880	235,340	563,550
$\Sigma y^4 =$	21,538	557,326	1,063,986	11,055,344	59,258,612	219,671,790
$\Sigma y^6 =$	451,330	43,524,910	83,093,010	1,889,941,040	17,749,376,420	101,885,895,150
$\Sigma y^8 =$	10,185,538	3,690,089,326	7,044,715,986	351,321,903,344	5,784,339,914,612	51,429,792,671,790
$\Sigma x^2y^2=$	12,100	84,700	592,900	6,150,400	32,947,600	122,102,500
$\Sigma x^2y^4=$	215,380	5,573,260	39,012,820	884,427,520	8,296,205,680	47,595,554,500
$\Sigma x^2y^6=$	4,513,300	435,249,100	3,046,743,700	151,195,283,200	2,484,912,698,800	22,075,277,282,500
$\Sigma x^4y^2=$	215,380	1,507,660	39,012,820	884,427,520	8,296,205,680	47,595,554,500
$\Sigma x^6y^2=$	4,513,300	31,593,100	3,046,743,700	151,195,283,200	2,484,912,698,800	22,075,277,282,500
$\Sigma x^4y^4=$	3,833,764	99,204,028	2,567,043,556	127,180,677,376	2,088,984,590,224	18,552,747,144,100

the various simplifying properties associated with rectangular distributions. The elements of the solution vectors are arranged according to the groups I, II, III, and IV to show the independence of these groups.

Figure 2 is used in the following way. Suppose it is desired to fit gravity data over such a grid by a plane surface

$$G(xy) = c_{00} + c_{10}x + c_{01}y.$$

It is necessary to compute the quantities $\sum g$, $\sum gx$, and $\sum gy$. $G(xy)$ may then be written immediately as

$$G(xy) = \frac{\sum g}{121} + \frac{\sum gx}{1,210}\,x + \frac{\sum gy}{1,210}\,y.$$

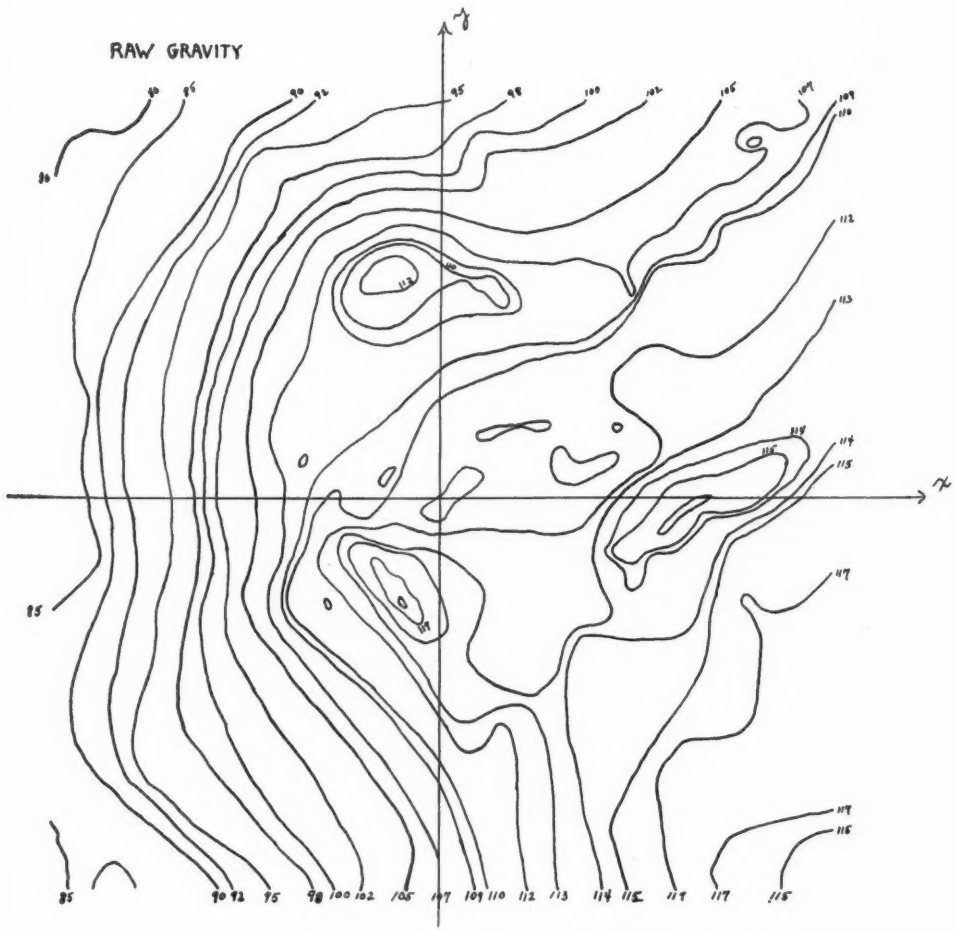

FIG. 3. Raw gravity to be analyzed.

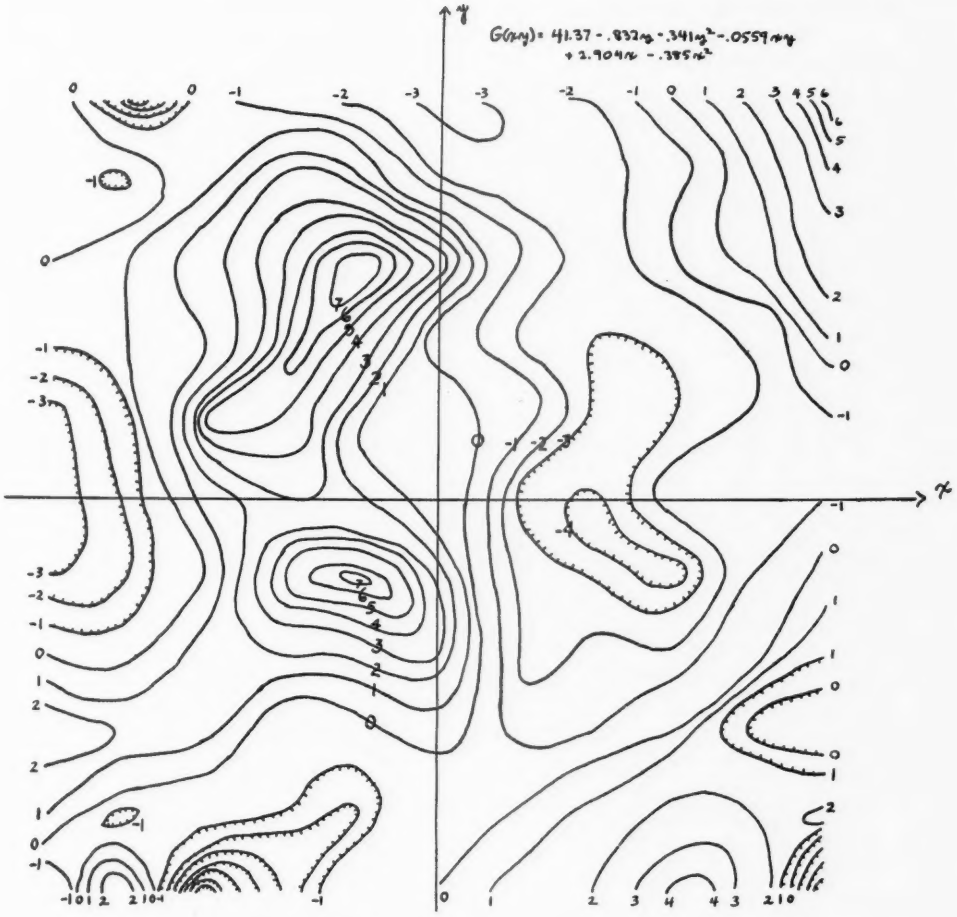

FIG. 4. Residual gravity with second order polynomial.

Following this, the equation must be solved at each point on the grid to determine the residuals. For higher order polynomials the determination of the c_{kl}'s is also quite rapid.

Figure 3 is a contour of gravity readings taken over a grid of this type. For these data, topographic corrections were known to be low order effects (approximately second order) and were not removed. Because of this, a first order polynomial was not used. Instead the data were fitted successively by polynomials of order 2, 3, and 4 as an experiment in removing the regional and topographic effects simultaneously. The resulting residual contours are shown in Figures 4, 5, and 6.

Without evaluating the contours individually, it seems that there is a closer similarity between them than might be expected. This similarity is better illustrated in Figure 7, which represents contours of the three polynomials themselves.

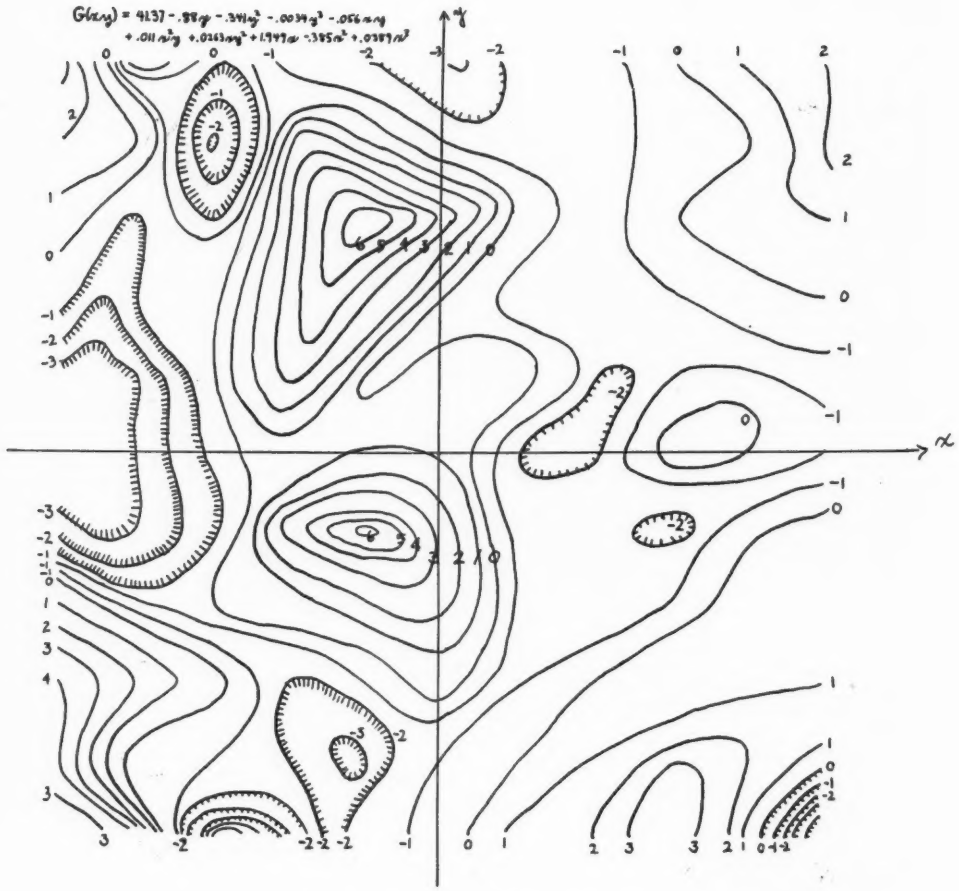

FIG. 5. Residual gravity with third order polynomial.

The figure points out that the regional (plus topographic) anomaly approximations were not rapidly affected by the addition of higher order terms. The indication here is that the true regional anomaly is lower than fourth order and that other anomalies are considerably higher order effects. In this situation the second or third order contours are probably to be preferred.

MACHINE COMPUTATIONS AND THE DENSITY PLOT

The preceding discussion has been concerned with reducing the problem of finding the solutions of normal equations to a minimum. There still remain the formation of the vector $[\sum g x^i y^j]$, the computation of the residuals, and the contouring of the results. These are all time consuming tasks. The author has been privileged to have the use of the Whirlwind I computer in his work at MIT and

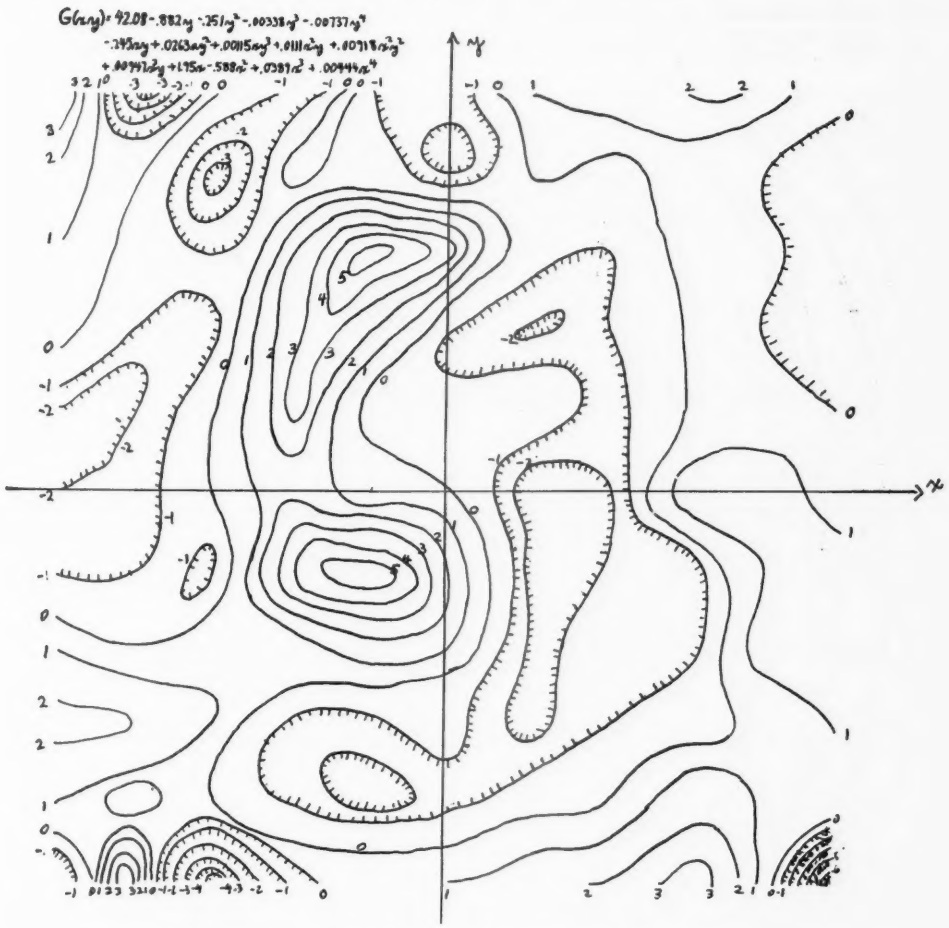

FIG. 6. Residual gravity with fourth order polynomial.

would like to illustrate ways in which machines of this nature can handle such problems.

Whirlwind I is a high speed digital computer of high reliability. It is equipped with a "delayed printer" form of output, by which computational results may be transferred rapidly to magnetic tape. Then, while the machine is computing on another problem, a Flexowriter types out the results from the tape. Results may also be removed on an oscilloscope, photographs being taken of the displays. These are especially useful features in problems where there is a high ratio of output to computation, such as the problem under discussion.

Figure 8 is a reproduction of the output form of a "program" which computes residuals over rectangular grids. The residuals are automatically typed out over the same rectangular pattern to allow contouring without transcribing. The

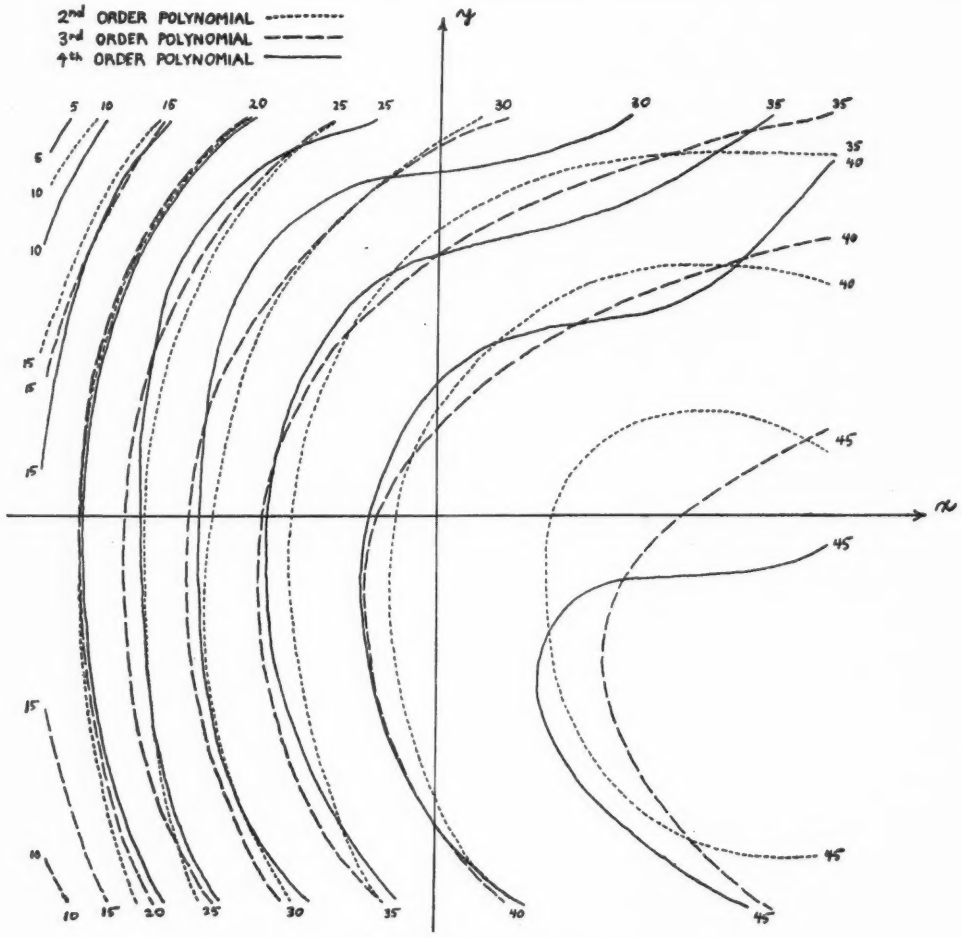

FIG. 7. Contours of the polynomials for Figures 4, 5, and 6.

machine time used in this case (these are the residuals of Figure 6) including input, computation, and recording the residuals on magnetic tape is less than one minute.

Using the oscilloscope it is possible to do a form of contouring directly. However, it is also possible to present the results in what might be called a density plot display. Within each little square surrounding a point on the scope (representing a point on the xy plane) is displayed a number of spots corresponding to the residual value at the point. Actually the number of spots displayed is logarithmically proportional to the residual because of the non-linearity of eye response to light intensity. The result is a shaded diagram in which the residual peaks stand out as white areas. Using a "program" which does this, a photograph of the residuals for the second order polynomial used elsewhere in this paper was

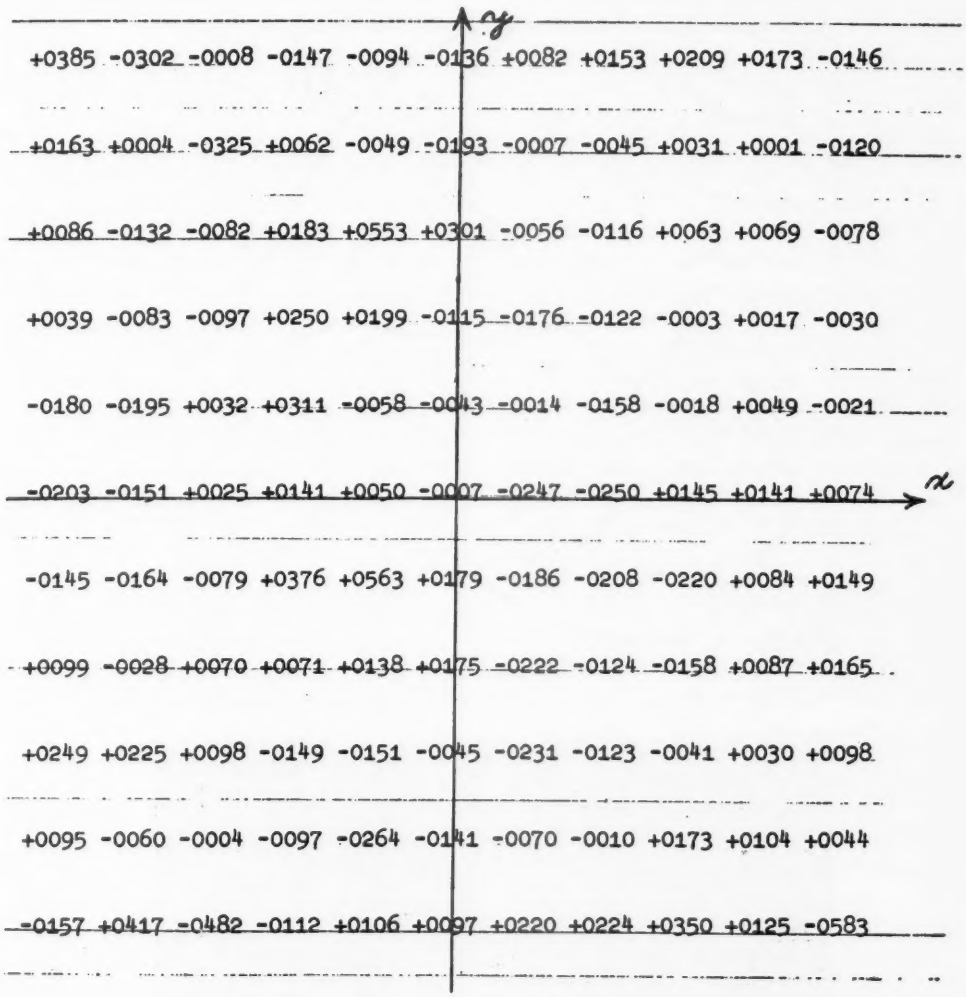

FIG. 8. Sample output of a program which computes residuals.

taken. It is shown in Figure 9 alongside of the corresponding contour map for comparison. The display takes about 25 seconds of machine time.

Residuals presented as density plots as in Figure 9 have immediate visual appeal and do not require the close examination that contours do. Furthermore the plot is unique and wandering contours in flat areas are avoided. It is apparent that the technique is not confined to gravity residuals but applies equally well to magnetic data or to any other problem involving two dimensional contours.

Further descriptions of Whirlwind are found in various issues of *Digital Computer News Letter*. Other features and coding details are described in Report R-196 of Electronic Computer Division, Servomechanisms Laboratory, MIT.

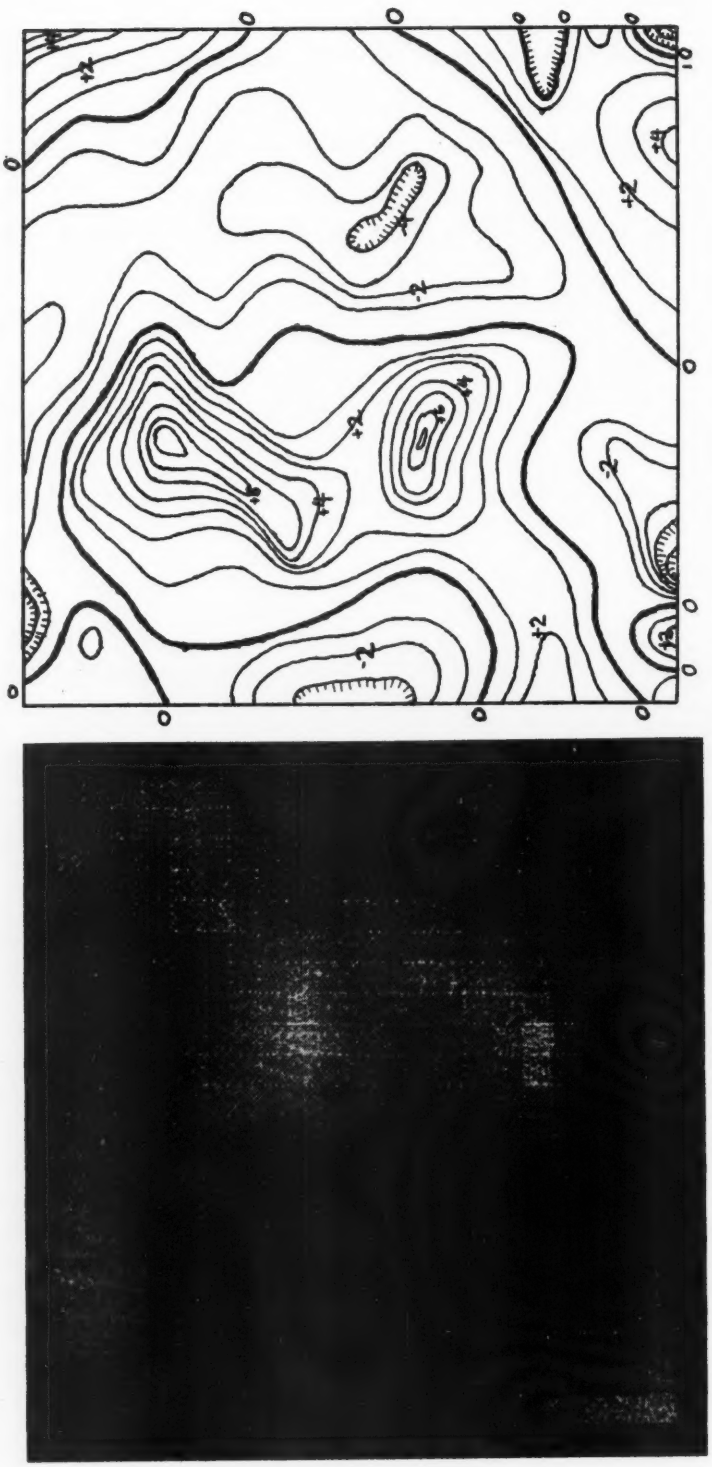

FIG. 9 The density plot display as compared with the more usual contour map.

CONCLUSIONS

The foregoing review of least squares polynomial fitting suggests a method of bringing polynomials of order greater than one within practical range. This is accomplished by a standardization of the pattern on which data are taken. For any pattern which is rectangular the solutions may be represented in the form of Figure 2.

As for density plotting, the author is convinced that digital computers have great versatility in treating geophysical problems. He presents this technique as an application of the digital computer which may not have been previously considered.

ACKNOWLEDGMENTS

The author is grateful to T. R. Madden for suggesting the least squares study. He wishes to acknowledge the assistance of M. K. Smith in developing the idea of density plotting. Thanks are due also to the personnel of the MIT Digital Computer Laboratory for their cooperation.

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AIRBORNE MAGNETOMETER PROFILE FROM PORTLAND, OREGON TO ALBUQUERQUE, NEW MEXICO*

W. B. AGOCS,† J. C. ROLLINS,† AND E. BANGS†

ABSTRACT

An airborne magnetometer profile of the variations of the earth's anomalous total magnetic field was obtained using a wing-tip magnetometer installation in a flight from Portland, Oregon to Albuquerque, New Mexico. The magnetic data were obtained by flying at barometric altitudes ranging from 7,000 to 10,000 feet above mean sea level.

The variations in the total magnetic field are tied to the known geology along the flight path, and the possible interpretations of the magnetic data are reviewed in light of the known general geology.

INTRODUCTION

In the course of a flight from Portland, Oregon to Albuquerque, New Mexico, in June 1953, an airborne magnetometer profile along the 1,635 mile course was recorded, and the results are presented herewith. The flight path, control points, and geology are shown in Figures 1 and 2.

A twin-engined Cessna UC-78, was used for the survey. The magnetometer elements were housed in a wing-tip nacelle. Magnetic effects from the plane were compensated.

The positional control of the magnetic profile was obtained from compass courses laid out in advance, and from observation of the towns located on the aeronautical charts.

The flight elevation was controlled by barometric level flying, and all flight elevations were changed in the vicinity of check points. Such changes were made as rapidly as possible so that the plane would attain the desired altitude without recourse to circling.

ELEVATION AND TOPOGRAPHIC CLEARANCE

The flight elevation, from Portland (control point 1) to Camp (control point 5) was maintained at 7,000 ft above mean sea level, and the topographic clearance ranged from 6,800 to 2,700 ft. From Jacksonville, Oregon (control point 6) to Walker Lake, Nevada (control point 22) the flight elevation was 9,000 ft with a topographic clearance varying from 8,500 ft to 1,100 ft. At Walker Lake the elevation was increased to 10,000 ft and maintained at this level to Las Vegas, Nevada (control point 31) and the topographic clearance varied from 1,800 ft to 8,000 ft. From Las Vegas to control point 34, the elevation was maintained at

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7,000 ft and increased to 8,000 ft from control point 34 to control point 36. From control points 36 to 38 the elevation was altered to 9,000 ft and decreased to 8,000 ft from controls 38 to 40, and decreased to 6,500 ft from control 40 to 41 at Glendale, Arizona. From Mesa, control point 42, to Tucson (control point 46) the elevation was 4,500 ft with topographic clearances varying from 3,000 ft to 800 ft. From Tucson, control point 47, to Albuquerque, control point 60, the flight eleva-

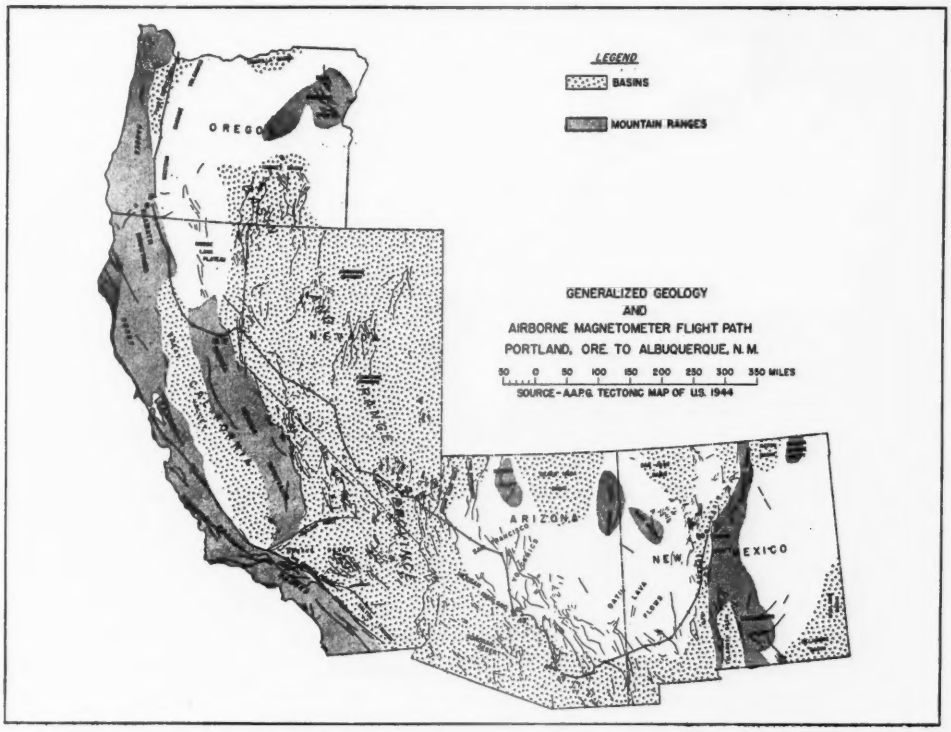

FIG. 1. Flight course and general geology along course of flight.

tion was maintained at 9,000 ft with topographic clearances ranging from 6,500 ft to 900 ft.

NORMAL OR REGIONAL CORRECTION

The magnetic profile has not been corrected for the normal, or regional, variation of the earth's total field. This normal variation is indicated by the "Regional Gradient" lines on Figures 3 to 8, so that these corrections may be made if desired.

The comparison of the earth's normal gradient with the general observed gradients will show the agreement between these two sets of data, excepting at a few local discontinuities which may be correlatable to "near surface" effects.

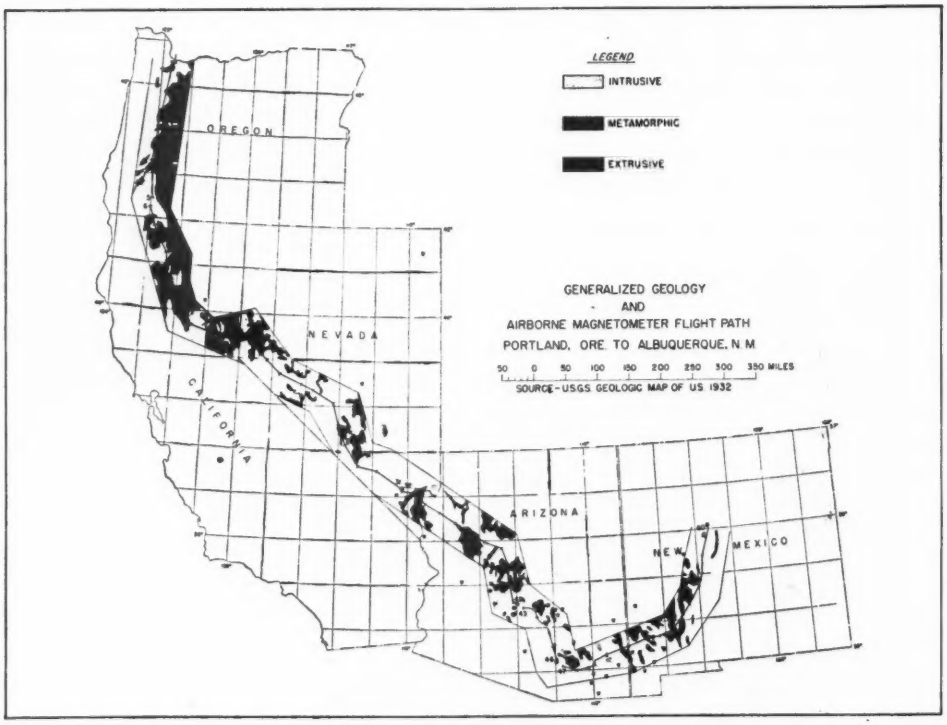

FIG. 2. Flight course and location of outcrops of igneous and metamorphic rocks along the course of flight.

GEOLOGY AND MAGNETICS

The profile from control points 1 to 4 (Figures 1, 2, and 3) roughly follows the contact between the Willamette Valley or Puget Depression on the west and the Cascade volcanics on the east. In the Portland-Salem area, basic sills and dikes have intruded the Tertiary, in addition to the profuse interbedded volcanics. The rocks of the Willamette Valley are Tertiary clastic sediments and volcanics; the section is about 20,000 feet thick, and it is probably underlain by the Cretaceous (Buddenhagen, 1941).

The magnetic profile from control points 1 to 5 (Figure 3) may be divided into two sections. From 1 to 2, the anomalies are sharp with an average deviation of 200 gammas, and a wave length of $2\frac{1}{2}$ miles. These anomalies are superimposed on major magnetic highs whose apices are located 50 miles, 75 miles, and 120 miles, respectively, south of Portland (control point 1) and they show deviations of 750, 650, and 480 gammas, respectively. The former sharp magnetic anomalies are due to the surface exposure of magnetic material of varying thickness, while the causes of the latter magnetic swells show depth ranges increasing from north to south of from 8 miles to 16 miles, sub-flight level. To the south of a point midway

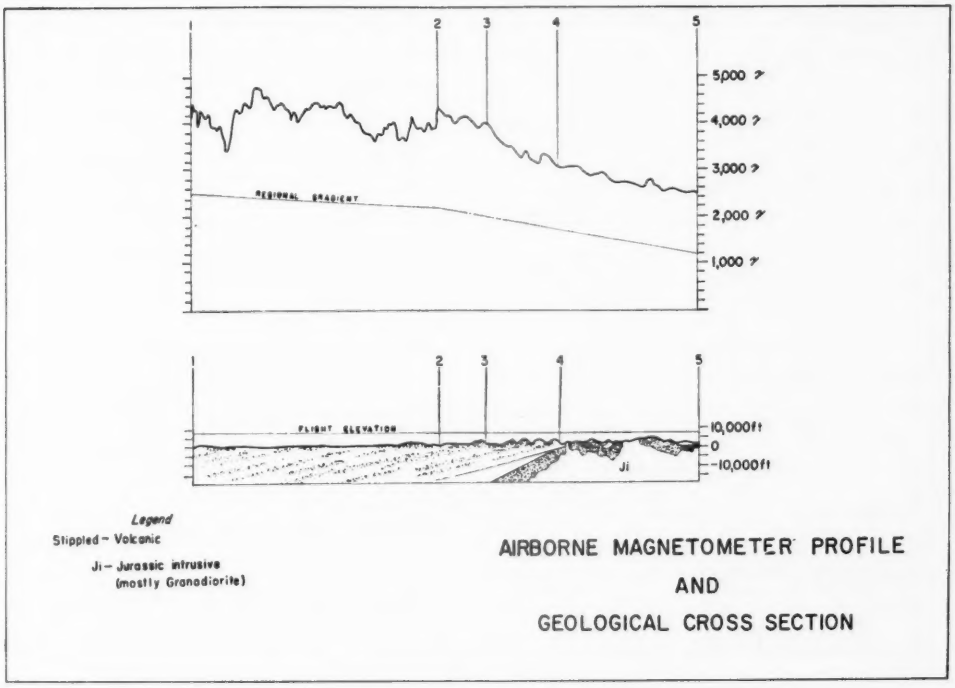

FIG. 3. Airborne magnetometer profile and generalized geologic cross-section from Portland to Camp, Oregon.

between control points 3 and 4, the observed general gradient is parallel to the normal earth's gradient, and the magnetic anomalies are *relatively* broad features.

At a point 17 miles south of control point 1 a negative anomaly of 300 gammas has been recorded. This marked deviation from a normal magnetic level may be attributed to a negative or inverse polarization, since its magnitude is equal to the positive deviations within the area.

The sharp magnetic discontinuity at control point 2 is probably indicative of a discontinuity of the volcanics.

The profile from control points 5 and 6 to control point 11, Figure 4, is along the western margin of the Klamath Range. About half the rocks exposed are granodiorites and other acidic igneous rocks intruded during the middle Jurassic Nevadan Orogeny, and the remainder are metamorphosed Paleozoic and Mesozoic rocks. The intrusive rock between control points 8 and 10 is an ultrabasic differentiate of the Sierra Batholith (Eardley, 1951, p. 255, and Geologic Map of California, 1941).

The magnetic anomalies from a point midway between control points 3 and 4 to control point 8 are similar, indicating that these anomalies are probably caused by the acidic intrusives and extrusives. However, the major positive anomaly zone from control point 8 to a point 10 miles north of control point 10

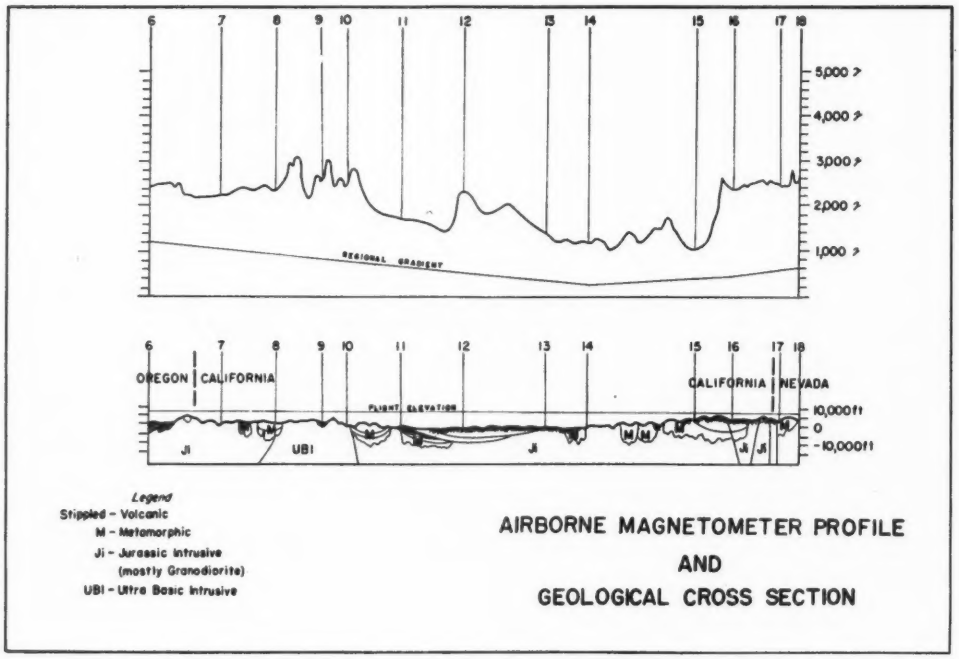

FIG. 4. Airborne magnetometer profile and generalized geologic cross-section from Medford, Oregon across northeastern California to Reno, Nevada.

is due to the outcrop of the ultrabasic phase of the Sierra Batholith.

The flight line between control points 11 and 13 is across the north end of the Sacramento Valley, which is a topographic and structural basin. The sedimentary section at this end of the valley reaches a thickness of ten or eleven thousand feet (Hobson, 1941). The basin is overlain by Tertiary and Quaternary volcanics at the southwestern fringe of the Modoc lava plateau.

The magnetic profile in the interval from control points 11 to 13 indicates gentle anomalies with the exception of the sharp discontinuity north of control point 12 which represents a change in level of 700 gammas. This change is probably due to a basic intrusive whose top is at a depth of 3 to $3\frac{1}{2}$ miles sub-flight level. The extent of this basic mass is about 28 miles along the control line.

The flight line passed over the northern end of the Sierra Nevadas between control points 13 and 18. The dominant rocks of the area are those of the granodiorite batholith, metamorphosed sediments of Paleozoic and Mesozoic age, and superincumbent Cenozoic extrusives.

The magnetic profile from control point 13 to midway between control points 15 and 16 shows magnetic anomalies which may be associated with buried basic igneous rocks whose magnetic anomalies are of the order of 300 gammas. However, east of control point 15 the magnetic field increases by 1,400 gammas, and

the anomalies become sharp and relatively shallow. This latter discontinuity is probably due to the outcrop of surface volcanics east of control point 15. The susceptibility contrast at this break is 0.00038 cgs units, possibly a rhyolite.

The flight path was across the western and southern part of the basin and Range Province from control points 19 to 33. The Basin and Range Province is structurally characterized by fault blocks and thrusts that form an intricate mosaic of rocks varying in age and type. The area is divided in central Nevada by the Manhattan Geanticline. The broad basins east and west of this feature are estimated to have maximum depths in excess of thirty thousand feet (Ten Eyck, 1941).

The magnetic control in the interval from control point 19 to control point 33 (Figures 5 and 6) is at approximately the same level as the magnetic "uplift" observed on the crossing of the Sierra Nevadas. Up to control point 21 the magnetic anomalies are similar to those observed west of Reno, but as one progresses toward control point 33, the anomaly amplitudes are reduced and their width is increased. In the interval from control points 28 to 31 the magnetic anomalies are practically featureless. In general, it is possible to conclude that the distance or depth to the cause of the magnetic anomalies is increasing, excepting in local

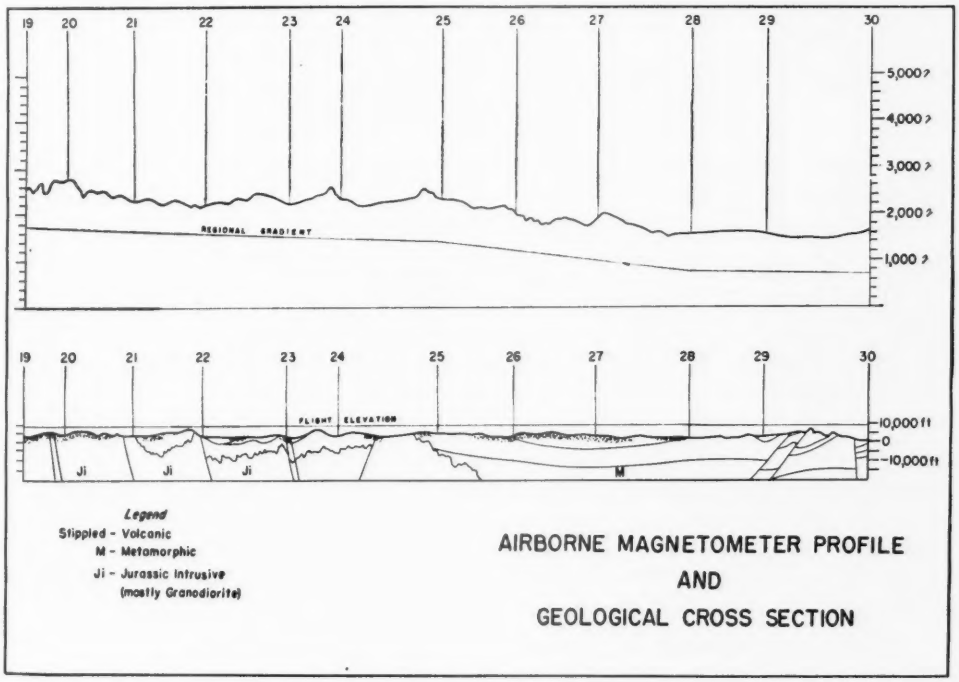

FIG. 5. Airborne magnetometer profile and generalized geologic cross-section from Reno to Las Vegas, Nevada.

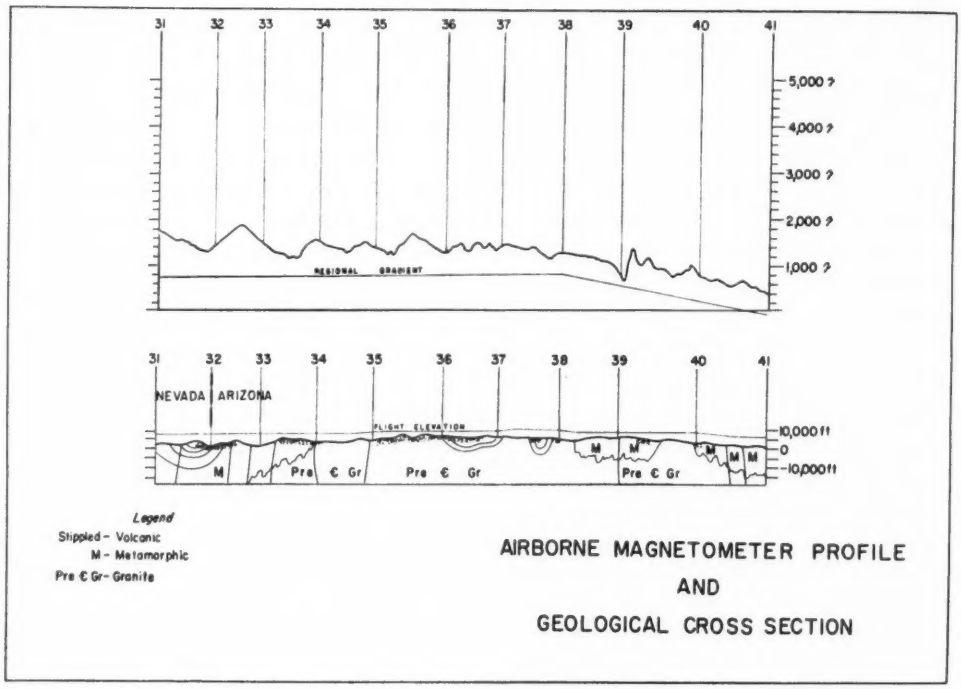

FIG. 6. Airborne magnetometer profile and generalized geologic cross-section from Las Vegas, Nevada to Glendale (Phoenix), Arizona.

zones where the igneous rocks are exposed or near the surface as indicated by sharper minor anomalies.

From control points 33 to 46 the flight passes over the Mexican Highlands, which is an area of igneous and metamorphic pre-Cambrian rocks. Faults are abundant in this complex. From control points 35 to 40 the flight was roughly along the boundary between the Mexican Highlands and the Colorado Plateau, which is capped by the San Francisco volcanic field, a group of irregular areas of basalt, andesite, and rhyolite (Eardley, 1951).

The magnetic profile in the interval from control point 33 to control point 35 (Figure 6) shows relatively broad but complex magnetic anomalies which are associated with the igneous and metamorphic rocks of the Mexican Highlands. Between control points 35 and 40, the sharp zones of minor magnetic anomaly are probably correlatable to the San Francisco volcanics. A major discontinuity in these volcanics is indicated by the sharp local positive and negative anomaly located south of control point 39.

A few small Paleozoic and Mesozoic basins were crossed in the interval from control points 47 to 50 (Figure 8). Magnetically, the interval from control point 48 to 49 appears to have the deepest source.

The flight line from control station 50 to 52 was across a group of minor sedi-

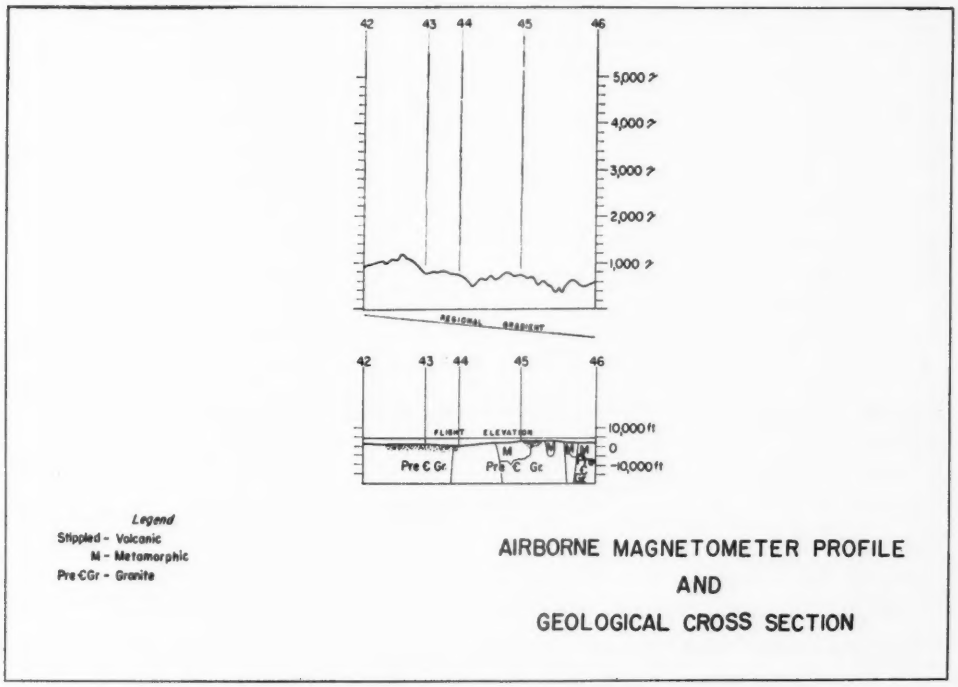

FIG. 7. Airborne magnetometer profile and generalized geologic cross-section from Mesa (Phoenix) to Tucson, Arizona.

mentary basins in southwestern New Mexico. These depressions contain severely faulted rocks of almost every period, and Tertiary intrusion has complicated the geology of the area (Rocky Mountain Assoc. of Geologists, 1941).

The flight crossed a few irregular lobes of the Datil lavas between control points 53 and 58. The magnetic indications of these zones are observed between control points 54 and 55, and 57 and 58 (Figure 8). In the former zone, a sharp magnetic anomaly is probably due to the termination of a relatively thick sheet of lavas.

The flight from control points 52 to 60 was across the axes of a series of structural basins coinciding with the Rio Grande Valley (Rocky Mountain Assoc. of Geologists, 1941). These are, from south to north, the Caballo, San Marcial, and Albuquerque Basins. The thicknesses of the former two basins are greater than 1,000 ft and the latter is more than 5,000 ft thick.

MINERALIZED ZONES

The flight passes over four metalogenic provinces as recognized by Bateman. The prominent metals being extracted from the ores of these provinces are copper, gold, silver, mercury, lead, zinc, molybdenum, chromium, and nickel.

Chromic iron ore deposits and *cinnabar* are found in the ultrabasic differen-

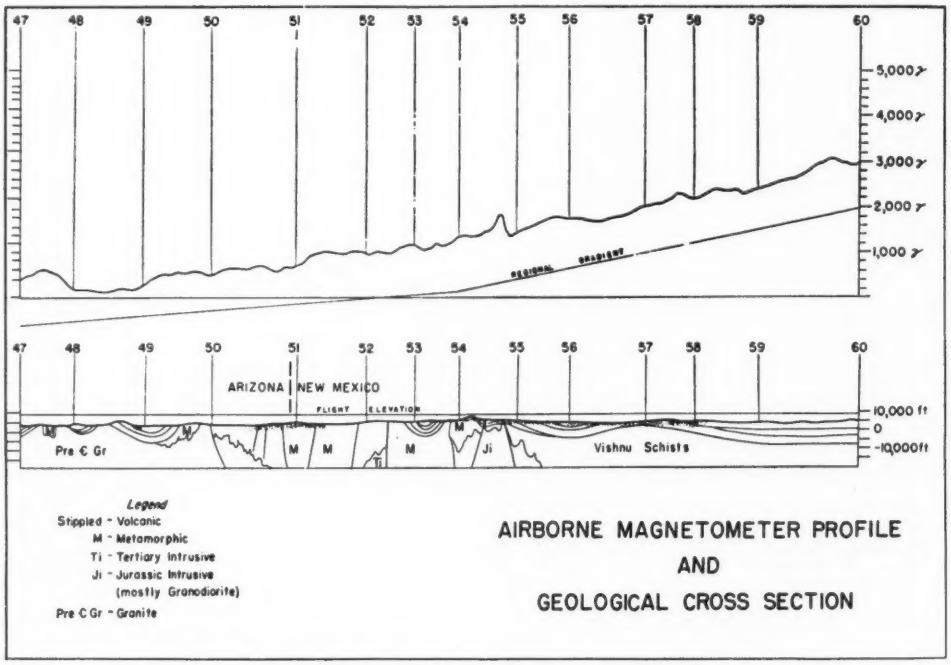

FIG. 8. Airborne magnetometer profile and generalized geologic cross-section from Tucson, Arizona to Albuquerque, New Mexico.

tiates of the Sierra Batholith. The magnetic expression of this feature is observed between control points 8 and 11. The local magnetic highs probably coincide with ultrabasic rocks.

Occurrences of *nickel* are known in the Klamath Mountains of Oregon near Riddle. The magnetic anomalies between control points 4 and 5 lie in this area.

The Pacific Coast *gold* deposits are associated with the batholiths of the Pacific Coast Ranges, Klamath Mountains, and the Sierra Nevada Mountains. The profile from control points 10 to 26 lies in the vicinity of these occurrences. The "Mother Lode" of California is located in the vicinity of control points 10 to 12; Grass Valley is in the vicinity of control point 14. The Mother Lode is a series of faults in steeply dipping slates, schists, and greenstones which contain chlorite and amphibole, and which are in altered tuffs and lavas. Grass Valley is a fissure vein associated with granodiorite plutons. The veins are parallel to the long axis of the plutons. Tonopah and Goldfield, Nevada lie between control points 24 at 26. The deposits in this latter area are associated with a dacite sill which intrudes andesite and contains most of the ore.

Iron ore is located near Heroult, California, near control points 8 and 10, and near Fierro, New Mexico, between control points 52 and 54. The former is a contact metamorphic deposit in limestone at the contact with diorite, and the latter is also a contact metamorphic product with monzonite porphyry.

Copper occurs in the vicinity of the flight line from control points 38 to 57. "Porphyry Coppers" are found at Ray, Chino, Miami, Inspiration, Moreno, and Ajo, Arizona and Santa Rita, New Mexico in the interval from control points 42 to 54, where the ores are associated with monzonite, quartz monzonite, or diorite porphyry intrusions; these intrusions are stocks or chonoliths which have entered along major tectonic breaks. The deposits at Bisbee, occurring in the vicinity of control points 48 to 51, are limestone replacement and contact metamorphic deposits resulting from intrusions by acid igneous rocks. The deposit at Jerome, Arizona, between control points 37 to 39, is a contact metamorphic deposit occurring at the contact between a diorite stock and the pre-Cambrian schists.

CONCLUSIONS

The control from this single profile is insufficient to lead to definite diagnostic conclusions concerning local structures and mineralization. Also the topographic clearance was too great for such details. However, the existing magnetic control does present regional anomalies which reflect crustal structures and major geologic provinces. Detailed studies of geology may be assisted by information of this nature.

ACKNOWLEDGMENTS

The authors wish to express their thanks to the personnel of Aero Service Corporation for their aid in assembling these data, and to Messrs. Virgil Kauffman and C. H. Frost for giving permission for their publication.

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ON THE RELATION BETWEEN TELLURIC CURRENTS AND THE EARTH'S MAGNETIC FIELD*

JAMES R. WAIT†

ABSTRACT

The validity of Cagniard's analysis of the behaviour of telluric earth currents is questioned in view of the fact that the harmonic components of the electric field and the magnetic field tangential to the ground are only proportional to one another if the fields are sufficiently slowly varying over the surface of the ground. His result is extended to include the effects of a layered ground with both conductivity and susceptibility variations. Finally the corresponding transient problem is solved for a two-layer horizontally stratified earth.

In a recent interesting and important paper by Cagniard (1953), the relation between telluric earth currents and variation of the earth's magnetic field is studied. In the present paper the validity of his results is discussed and several extensions to the theory are pointed out.

The impedance concept in electromagnetism, as first disclosed so lucidly by Schelkunoff (1938), is well suited to this type of problem. If the electric and magnetic forces tangential to a surface S at a point P are mutually perpendicular, the ratio of the tangential electric force to the tangential magnetic force is termed the field impedance normal to S at P. In general the tangential electric and magnetic forces are not perpendicular so that the field impedance does not exist; even if it does exist, it may depend upon the system of sources by which the fields have been set up (Monteath, 1951).

Let the x, y plane be the boundary between two semi-infinite homogeneous media, the fields being set up by sources in the upper medium. It can be shown that in this plane the tangential electric fields E_x and E_y are related to the tangential magnetic fields by

$$\left.\begin{aligned} E_x &= \eta H_y + \frac{\eta}{2\gamma^2}\left(\frac{\partial^2 H_y}{\partial y^2} - \frac{\partial^2 H_y}{\partial x^2} + 2\frac{\partial^2 H_x}{\partial x \partial y}\right) + \text{terms in } \gamma^{-4}, \text{ etc.} \\ \text{and} \\ -E_y &= \eta H_x + \frac{\eta}{2\gamma^2}\left(\frac{\partial^2 H_x}{\partial x^2} - \frac{\partial^2 H_x}{\partial y^2} + 2\frac{\partial^2 H_y}{\partial y \partial x}\right) + \text{terms in } \gamma^{-4}, \text{ etc.} \end{aligned}\right\} \quad (1)$$

where, $\gamma = i\sigma\mu\omega - \epsilon\mu\omega^2$ is the intrinsic propagation constant of the lower medium and $\eta = i\mu\omega/\gamma$ is its intrinsic characteristic impedance. The constants σ, ϵ, μ are the conductivity, dielectric constant, and permeability of the lower medium.

Equation (1) was obtained by regarding the distribution of H_x and H_y over

* Manuscript received by the Editor October 29, 1953.

† Radio Physics Laboratory, Defence Research Board, Ottawa, Canada.

the x, y plane as an aperture distribution giving rise to an angular spectrum of plane waves (Monteath, 1951). If H_x and H_y vary sufficiently slowly over the x, y plane, or if γ is sufficiently large, only the first term in each of the formulae need be retained. For example, if the frequency is 0.1 cycle (a period of 10 sec) and the conductivity of the ground is 10^{-1} mho/meter then $|1/\gamma| = 35$ kilometers. Then for this case if H_x and H_y do not change greatly between points 35 km apart, the terms in γ^{-2}, etc. may be neglected and equation (1) becomes:

$$E_x \approx \eta H_y$$
$$E_y \approx -\eta H_x. \tag{2}$$

Thus the field impedance normal to the boundary exists and is equal to the intrinsic impedance of the lower medium. For periods longer than about 10 seconds it is probable that H_x and H_y vary by an appreciable amount in the distance corresponding to $|\gamma^{-1}|$ since it is believed that the sources of the variations of the earth's magnetic field are at heights of the order of 100 kilometres as evidenced from rocket measurements (Mitra, 1952, p. 574; Baker and Martyn, 1952). This would vary considerably during periods of magnetic activity.

Equation (2) is exact if the sources in the upper medium (air) give rise to plane waves incident normally on the lower medium (ground). For most cases the sources in the atmosphere do not give rise to normally incident plane waves. Cagniard recognizes this fact and also arrives eventually at equations exactly equivalent to equation (2). He does not recognize, however, that the plane wave spectrum can contain plane waves with a complex angle of incidence α. He states that $\sin^2 \alpha$ is never greater than unity in magnitude, which is of course incorrect. The limitation that H_x and H_y should not vary greatly in a distance $|\gamma^{-1}|$ is therefore not evident from Cagniard's analysis.

When the ground is horizontally stratified, consisting of say an upper stratum of thickness h with an intrinsic propagation constant γ_1 and intrinsic impedance η_1 and a lower stratum of infinite thickness with constants γ_2 and η_2, the surface impedance is given by

$$\eta = \eta_1 \frac{\eta_2 + \eta_1 \tanh(\gamma_1 h)}{\eta_1 + \eta_2 \tanh(\gamma_1 h)}. \tag{3}$$

This formula can be arrived at directly by considering the analogous transmission line problem (Schelkunoff, 1938). The equivalent line is of length h with a propagation constant γ_1 and characteristic impedance η_1 and is terminated in an impedance whose value is η_2. The input impedance of the line is then η as given by equation (3), which can now be written in terms of the conductivities σ_1 and σ_2, and magnetic permeabilities μ_1 and μ_2 of the upper and lower strata as follows:

$$\eta = \eta_1 Q \tag{4}$$

where

$$Q = \frac{(\mu_2\sigma_1/\mu_1\sigma_2)^{1/2} + \tanh\,(i\sigma_1\mu_1\omega)^{1/2}h}{1 + (\mu_2\sigma_1/\mu_1\sigma_2)^{1/2}\tanh\,(i\sigma_1\mu_1\omega)^{1/2}h}$$

and it has been assumed that $\epsilon_1\omega \ll \sigma_1$ and $\epsilon_2\omega \ll \sigma_2$. This equation now reduces to Cagniard's equation (30) for the special case when the permeability contrast between the strata is zero (i.e. $\mu_1 = \mu_2 - \mu_0$). It is therefore pointed out that for cases of formations having magnetic susceptibility, ratios σ_2/σ_1, given in his Figures 7 and 8, should be replaced by the ratio $\mu_1\sigma_2/\mu_2\sigma_1$, and the horizontal scale (inverse frequency) should be shifted to the left by a factor μ_2/μ_1.

To apply Cagniard's results to interpretation of sub-surface stratification it is necessary to carry out a harmonic analysis of both the electric field function $e_x(t)$ and the magnetic field function $h_y(t)$. The harmonic components $E_x(\omega)$ and $H_y(\omega)$ at an angular frequency ω are then compared to obtain the surface impedance function $\eta(\omega)$. Apparently this procedure requires a fair amount of labor unless the analysis be carried out by electronic means. A suggested alternative is to examine the relation between the time functions $e_x(t)$ and $h_y(t)$ directly.

If the magnetic field $h_y(t)$ is in the form of a step-function, that is, it suddenly changes from one level H_0 to another level $H_0 + \Delta H_0$ at $t = 0$ then the frequency spectrum $H_y(\omega)$ associated with this change is

$$H_y(\omega) = \int_{-\infty}^{+\infty} h_y(t)e^{-i\omega t}dt = \int_0^{\infty} \Delta H_0 e^{-i\omega t}dt = \frac{\Delta H_0}{i\omega}. \tag{5}$$

The corresponding frequency spectrum of the tangential electric field is then given by:

$$E_x(\omega) = \eta(\omega)\Delta H_0/i\omega \ .$$

The frequency function $\eta(\omega)$ is given by equation (3) for the two-layer ground and it can be rewritten in the following form.

$$\eta(\omega) = \frac{i\mu_1\omega}{\gamma_1}\left[1 + 2\sum_{n=1}^{\infty}\left(\frac{1-\beta}{1+\beta}\right)^n e^{-2n\gamma_1 h}\right] \tag{6}$$

where $\beta = (\mu_1\sigma_2/\mu_2\sigma_1)^{1/2}$. The time function $e_x(t)$ for the tangential electric field is then given by:

$$e_x(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} E_x(\omega)e^{-i\omega t}d\omega$$

$$= \frac{1}{2\pi}\left(\frac{\mu}{\sigma}\right)^{1/2}\Delta H_0 \int_{-\infty}^{+\infty}\left[\frac{1}{(i\omega)^{1/2}} + 2\sum_{1}^{\infty}\left(\frac{1-\beta}{1+\beta}\right)^n \frac{e^{-2n\alpha(i\omega)^{1/2}}}{(i\omega)^{1/2}}\right]e^{i\omega t}d\omega. \tag{7}$$

These integrals are of a known type (Campbell and Foster, 1948, p. 93, formula no. 807) so the integrations can be readily carried out to yield

$$e_x(t) = F(T)/\pi^{1/2}\sigma h$$

where

$$F(T) = T^{-1/2}\sum_{n=1}^{\infty}\left[1 + 2\left(\frac{1-\beta}{1+\beta}\right)^n e^{-n^2/T}\right] \tag{8}$$

and

$$T = t/\alpha^2 = t/\sigma_1\mu_1 h^2.$$

The function $F(T)$ is therefore characteristic of the shape of the electric field time function. It is plotted in Figure 1 as a function of the normalized time factor T. The case where $\beta = 1$ corresponds, of course, to the homogeneous ground where the electric field decays as $T^{-1/2}$. It is noted that for highly conducting lower layers $e_x(t)$ decays more rapidly than for the homogeneous ground. Conversely, if the lower layer is very poorly conducting the decay is somewhat slower.

The corresponding electric field function $e_x(t)$ for any other type of magnetic

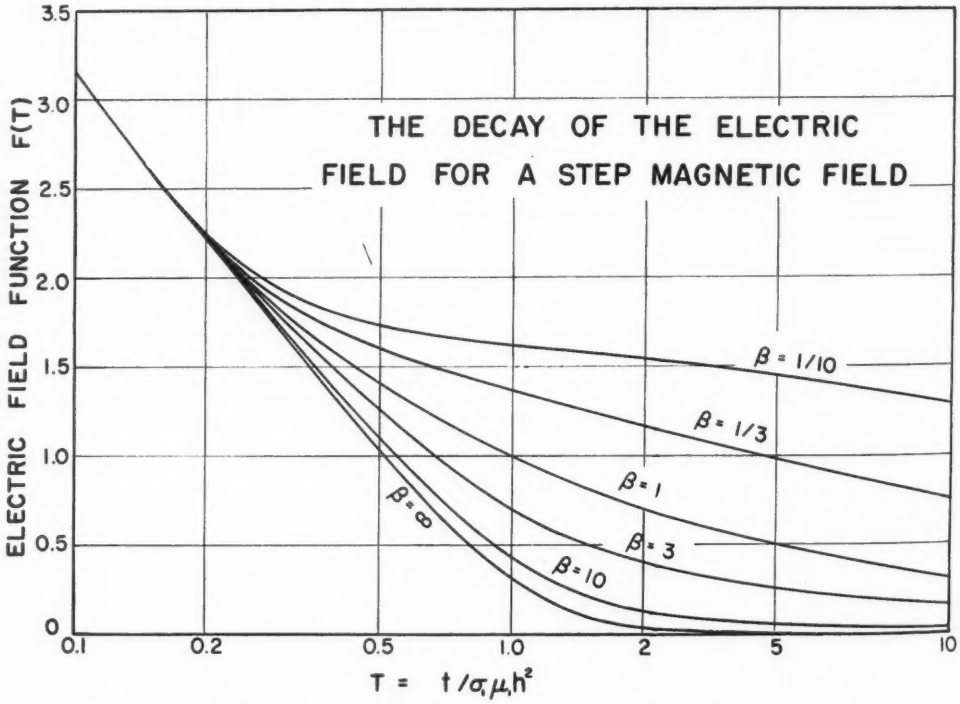

FIG. 1. Electric field variation with time for two-layered earth when magnetic field varies stepwise at $t=0$. The parameter $\beta = (\mu_1\sigma_2/\mu_2\sigma_1)^{1/2}$ where σ_1 and μ_1 are conductivity and magnetic permeability, respectively, of the upper layer, σ_2 and μ_2 of the lower layer.

field function $H_y(t)$ can be obtained in a similar manner. For example if the magnetic field is suddenly decreased in value by an amount ΔH_0 at time $t=0$ and then is re-established at $t=t_1$, the corresponding electric field $e_{x_1}(t)$ is given by

$$e_{x_1}(t) = e_x(t - t_1) - e_x(t)$$

where $e_x(t)$ is a step-function response given by equation (8).

For a magnetic field function $\bar{h}(t)$ given by

$$\bar{h}(t) = H_0 + \Delta H_0 f(t) \quad \text{for} \quad t > 0$$
$$= H_0 \quad \text{for} \quad t < 0$$

then the corresponding electric field function $\bar{e}_x(t)$ is expressed in terms of the step-function response $e_x(t)$ by:

$$\bar{e}_x(t) = \frac{d}{dt} \int_0^t f(t - \tau) e_x(\tau) d\tau.$$

The limitation that H_x (and H_y) varies slowly over the x, y plane also applies to the transient case. An equivalent statement is that H_x should not vary appreciably in a distance $(t/2\pi\sigma\mu)^{1/2}$. This means that the transient curves for $e_x(t)$ are probably not valid for any value of t greater than about 10 seconds.

I would like to thank Mr. D. A. Trumpler for his assistance with the calculations for Figure 1.

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CORRESPONDENCE BETWEEN PROF. CAGNIARD AND DR. WAIT

Before submitting the manuscript of the paper above to GEOPHYSICS, Dr. Wait sent a copy of it to Prof. Cagniard in France. The correspondence between them that followed has been made available by its authors for publication along with the paper and the letters that were exchanged are presented herewith. Acknowledgment is made to Dr. Robert G. Van Nostrand for translating Prof. Cagniard's letters.—THE EDITOR

Paris
24 October, 1953

Dr. James R. Wait
Defence Research Board
Ottawa, Canada

Dear Sir:

I have only recently received your interesting work for which I thank you very much. I assure you that I have not yet had the necessary time to study carefully its contents nor to refer to the bibliographic references which you cite. However, I do not want to delay giving you my first impressions.

With respect to transients, I stated (GEOPHYSICS, XVIII, p. 611) that I did not believe that they present great practical interest. It is to be understood that it would please me if you were to find a convenient and effective interpretive method based upon them. But, until I can be convinced of a better technique, I prefer the harmonic analysis and the use of the notion of apparent resistivity. Do not reproach me for not yet having told everything nor for not yet having explained the means by which I envisage making automatically the analysis in question. I am not in a position at present to furnish the details of the apparatus which I use to this end.

My calculations depend on the dual hypothesis of a uniform telluric sheet and a horizontally stratified geologic structure. They are, of course, only approximations. The merit of your work, merit which I appreciate greatly, is to furnish a critique of the value of this approximation. However, I would be very happy if you would show me how you establish equation (1) so that I can judge the hypothesis upon which it is founded. It would be equally agreeable to me if you would publish that at some time or another.

I would also like to make two remarks to you:

1. In the example which I have taken of a plane incident wave, I had no other aim than to show how very diverse causes could give place to the flow of the same type of current sheet in the earth. Since I considered only real plane waves, waves of the physicist and not those of the mathematician, my angles were real and I was not "incorrect" in stating that the absolute value of their sines was less than 1. In your case, you chose to consider a source situated at a finite distance and, following Weyl, to decompose the dipole emission into plane waves which are only mathematical abstractions and for which arise complex angles. I do not reproach you (for this approach) but do not criticize me for what I am doing; we are not treating the same problem.

2. Your argument concerning the lack of uniformity of telluric sheets seems to me to be open to criticism on the ground that magneto-telluric perturbations found at a given place are certainly not emitted by some isolated dipole situated in the ionosphere near the zenith. One would not explain then all of the remarkable uniformity of telluric sheets, a uniformity which is not simply a point of view nor a more or less adventuresome hypothesis but a proven fact of daily experience. When we record simultaneously in the Paris region and in the Midi of France, at two stations separated by 600 kilometers, over geologic structures which have absolutely nothing in common, rapid variation (a few seconds to a few minutes) of the horizontal components of the magnetic field, the two graphs obtained are striking in their near identity. Telluric recordings made simultaneously in France, Morocco, and Madagascar are certainly not identical—which would be contradictory—but never the less present an indisputable "family resemblance." All of this proves, if it is necessary, that magneto-telluric perturbations are not generated by isolated dipoles but by vast systems of ionospheric electric currents whose dimensions are on a global scale. The altitude of these sheets of ionospheric current can very well be of the order of only ten kilometers without introducing very much distortion in the uniformity of the telluric sheet over distances of several tens of kilometers.

I am sending a copy of this letter to Dr. Milton Dobrin. I thank you again for the interest that

you have shown in my work and the useful additions which you have made to it. Until I hear from you again, please accept, dear sir, my best wishes.

L. CAGNIARD
397, Rue Vaugirard
Paris, France.

Defence Research Telecommunications
Establishment,
Radio Physics Laboratory,
Defence Research Board,
Shirley Bay,
Ottawa, Ontario.
October 29, 1953

Professor Louis Cagniard,
397 Rue de Vaugirard,
Paris 15,
France.

Dear Professor Cagniard:

Thank you for comments on my note entitled "On the Relation Between Telluric Currents and the Earth's Magnetic Field." I am glad that you found this of interest.

I agree that the harmonic analysis of the earth current and the tangential magnetic field records would lead to a more refined method of interpretation if the Fourier components could be extracted by electronic means. In any case the transient and the frequency response data are equivalent from a mathematical standpoint. In addition, I believe that the "raw data" from the field records could be examined directly and compared to the idealized transient curves to ascertain quickly the general nature of the crustal layers.

I don't believe there is any doubt as to the existence of complex angles of incidence in the plane wave spectrum of radiation from a dipolar source. This question has been discussed at length by Booker and Clemmow.[1] Of course at large distances from the dipole the wave front is almost plane and the angle of incidence corresponds to the angle between the line of sight and the vertical. At shorter distances the field of the dipole becomes very different. The E and H fields are no longer mutually perpendicular to the radial direction and they are not related by the characteristic impedance of free space. In this case the spectrum in terms of plane waves contains complex angles of incidence so that $\sin^2 \alpha$ is not always less than unity. Of course, if the source were a current sheet of infinite extent and uniform in amplitude and phase, the emanating radiation, obtained by integrating over all the horizontal electric dipoles, would be a normally incident plane wave.

The current system in the upper atmosphere giving rise to short period (less than 60 sec) variations of the magnetic such as "micro pulsations" are confined to a limited region as observed by several investigators.[2,3,4] In this case the infinite sheet representation is not permissible. It would seem reasonable that the currents could be represented by a finite distribution of electric and magnetic dipoles and therefore one must admit complex angles of incidence. On the other hand there have been short period (5 to 10 sec) pulsations of small amplitude reported,[5] that do occur simultaneously over large parts of the world at lower and middle latitudes. At northern latitudes, however, the short period variations are generally due to local conditions in the ionosphere. In any case, it would

always be necessary to ensure that the magnetic field components do not change appreciably in a distance equal to the reciprocal of the propagation constant of the ground.

At your request I shall outline briefly the derivation[6] of equation (1) in my note.

A rectangular coordinate system is employed with the (x, y) plane coinciding with the ground and the z axis pointing downward. The ground is assumed to be homogeneous with electrical constants σ, ϵ, and μ. The field component H_z (and H_y) in the ground can be set up as a superposition of elementary waves so that

$$H_z(x, y, z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(K_1, K_2)e^{-i(K_1x+K_2y+K_3z)}(K_1/K)dK_1dK_2$$

where $f(K_1, K_2)$ is an aperature distribution and

$$K_1^2 + K_2^2 + K_3^2 = \omega^2\mu\epsilon - i\sigma\mu\omega = K^2.$$

The electric field E_y is then given by

$$E_y = \frac{1}{\sigma + i\omega\epsilon}\frac{\partial H_z}{\partial z}\Bigg]_{z=0} \text{ in the plane } z = 0.$$

It is noted that under the integral sign

$$\frac{\partial}{\partial z} = -iK_3 = -i\sqrt{K^2 - (K_1^2 + K_2^2)}$$

which can be expanded in a Taylor series as

$$\frac{\partial}{\partial z} = -iK\left[1 - \frac{K_1^2 + K_2^2}{2K^2} + O\left(\frac{1}{K^4}\right)\right].$$

The electric field tangential to the ground can then be written

$$E_y(x, y, 0) = -\eta\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left[1 - \frac{1}{2K^2}(K_1^2 + K_2^2) + \cdots\right]f(K_1, K_2)e^{-i(K_1x+K_2y)}(K_1/K)dK_1dK_2$$

which is equivalent to

$$-E_y = \eta H_x + \frac{\eta}{2K^2}\left(\frac{\partial^2 H_x}{\partial x^2} - \frac{\partial^2 H_y}{\partial y^2} + 2\frac{\partial^2 H_y}{\partial x\partial y}\right) + O\left(\frac{1}{K^4}\right).$$

A similar equation relates E_x and H_y in the plane $z=0$.

A more rigorous derivation of these relations[6] will appear in the *Journal of Applied Physics* in a forthcoming paper by W. J. Surtees and myself. I am also sending a copy of this letter to Dr. Dobrin.

Yours very truly,

JAMES R. WAIT

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Paris
16 November, 1953

Dr. James R. Wait
Defence Research Telecommunications Establishment
Ottawa, Ontario

Dear Sir:

Thank you for your last letter of October 29, 1953 and for the interesting proof which you have given me. I will make a brief reference to your work in the chapter "Electricité Tellurique" which Prof. Bartels of Gottingen has requested me to write for the next edition of *Handbuch der Physik*.

I am entirely in accord with you except regarding the question of the micropulsations being limited to a very restricted region. Only yesterday, M. Migaux, director of the Compagnie Générale de Geophysique, the man who "sees" the most micropulsations, told me that they do not exist except where there are industrial disturbances. Along with St. Thomas, we have to see to believe.

Please accept, dear Dr. Wait, this expression of my best wishes.

L. CAGNIARD
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MUTUAL COUPLING OF LOOPS LYING ON THE GROUND*

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ABSTRACT

The theory of a method to measure electrical ground constants by mutual coupling of loops is outlined. Curves are given in parametric form showing the dependence of the mutual impedance on conductivity, dielectric constant, frequency, and separation. An expression is derived in the appendix for the field of a circular wire loop laid on a homogeneous conducting ground.

INTRODUCTION

A means is proposed to determine the effective conductivity and diele tric constant of the ground by the measurement of the mutual coupling of two small single-turn loops lying on or near the surface of the ground. A theoretical analysis is therefore desirable. An idealized homogeneous flat earth is assumed with electrical properties that are isotropic and linear.

OUTLINE OF THEORY

An expression has been derived previously by the author (Wait, 1952) for the mutual impedance between two small circular wire loops lying on the surface of the earth. One loop is of area A_1, the other of area A_2, the distance between loop centers is ρ. The air has a dielectric constant ϵ_0 and a magnetic permeability μ_0. The homogeneous flat earth has a dielectric constant ϵ, a magnetic permeability μ_0 and a finite conductivity σ. All quantities are in M.K.S. units. A time factor $e^{i\omega t}$ is implied.

The mutual impedance Z for a frequency $\omega/2\pi$ is given as follows.

$$Z/Z_0 = 2(\gamma_0^2 - \gamma^2)^{-1}\rho^{-2}[(9 + 9\gamma\rho + 4\gamma^2\rho^2 + \gamma^3\rho^3)e^{-\gamma\rho} - (9 + 9\gamma_0\rho + 4\gamma_0^2\rho^2 + \gamma_0^3\rho^3)e^{-\gamma_0\rho}] \qquad (1)$$

where

$$Z_0 = \frac{A_1 A_2 i\mu\omega}{4\pi\rho^3},$$

$$\gamma = [i\sigma\mu_0\omega - \epsilon\mu_0\omega^2]^{1/2},$$

and

$$\gamma_0 = i(\epsilon_0\mu_0)^{1/2}\omega.$$

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This formula is simplified somewhat if the following inequality is valid:

$$|\gamma_0\rho| = (\epsilon_0\mu_0)^{1/2}\omega\rho \ll 1;$$

then

$$Z/Z_0 = 2\gamma^{-2}\rho^{-2}[9 - (9 + 9\gamma\rho + 4\gamma^2\rho^2 + \gamma^3\rho^3)e^{-\gamma\rho}]. \tag{2}$$

This approximation assumes that the spacing ρ of the loops is much less than a

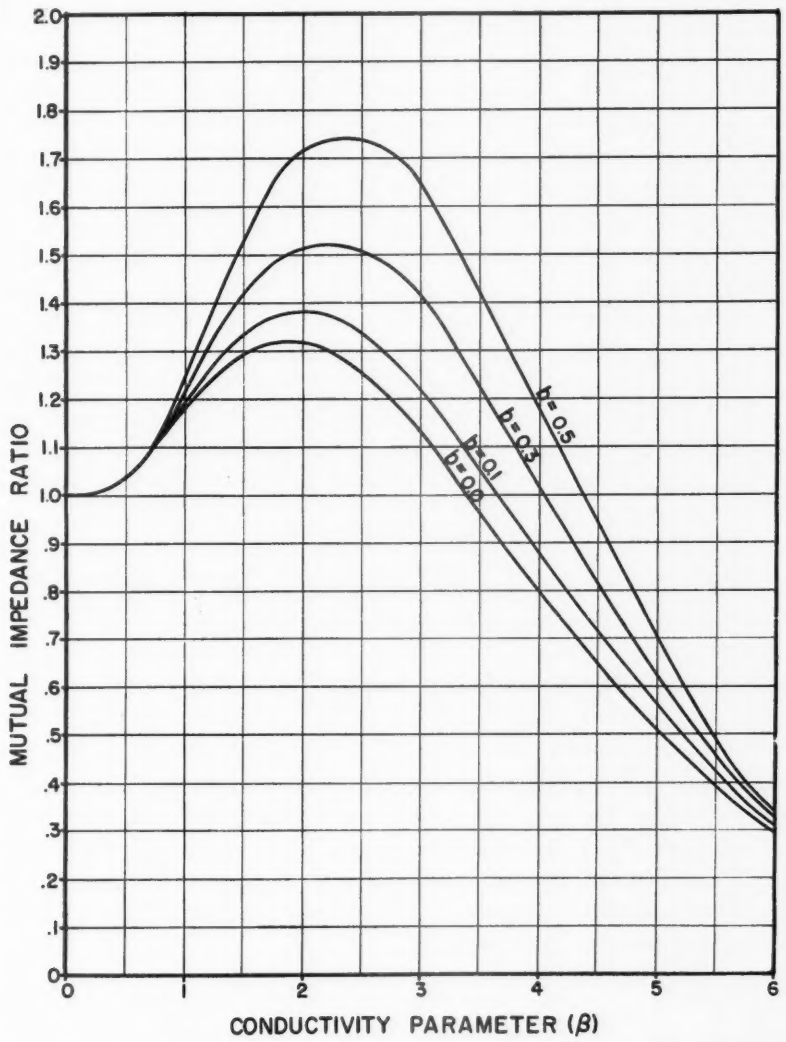

FIG. 1. The Mutual Impedance Ratio $|Z/Z_0|$ plotted as a function of the conductivity parameter $\beta(=(\sigma\mu\omega/2)^{1/2}\rho)$, for two small wire loops lying on a homogeneous ground, for various values of $b(=\epsilon\omega/\sigma)$.

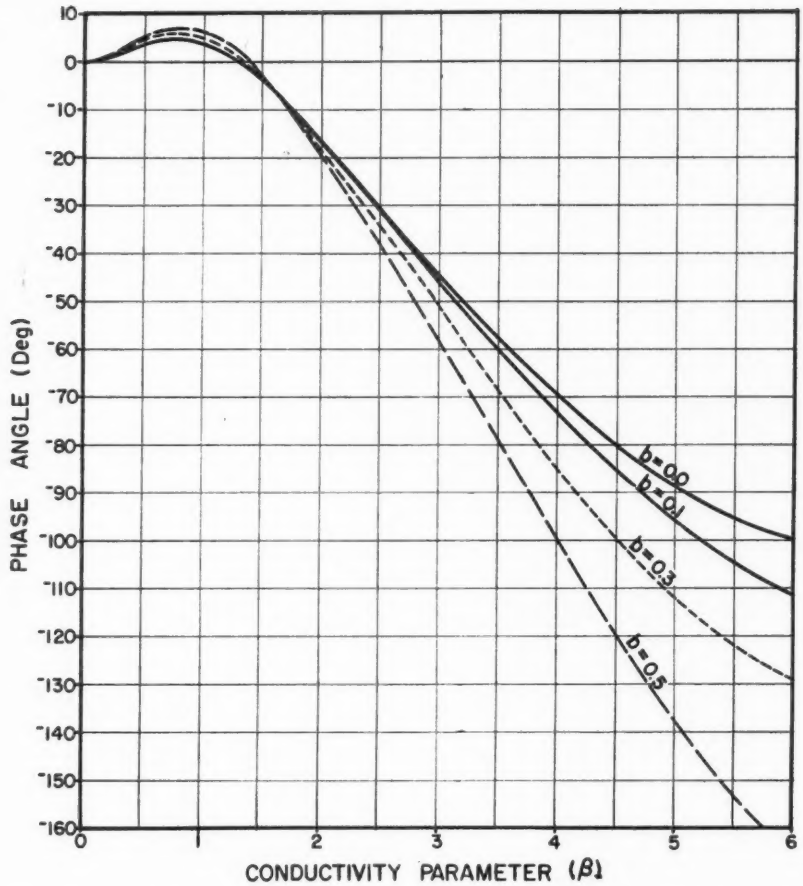

FIG. 2. The phase ϕ of the mutual impedance ratio as a function of the conductivity parameter β for various values of b.

free-space wavelength at the frequency $\omega/2\pi$. An alternative derivation of equation (2) is given in the appendix, which shows that this equation is valid to an error of less than 1% if the separation ρ is at least ten times the radius of the loops. It is also seen that if $|\gamma\rho|$ approaches zero, the ratio Z/Z_0 approaches unity. Z_0 is the mutual coupling between coplanar loops in an insulating region when the spacing is much less than a wavelength.

The factor $\gamma\rho$ may be written in the following form:

$$\gamma\rho = (1 + i)\beta(1 + ib)^{1/2}$$

where

$$\beta = (\sigma\mu\omega/2)^{1/2} \quad \text{and} \quad b = \epsilon\omega/\sigma.$$

The complex ratio Z/Z_0 is now written

$$Z/Z_0 = |Z/Z_0|\, e^{i\phi}. \tag{3}$$

The magnitude of the ratio $|Z/Z_0|$ and the phase angle ϕ of the ratio is plotted against the parameter β for several values of the parameter b in Figures 1 and 2 respectively.

APPLICATION OF RESULT

The transfer mutual impedance ratio between small loops is then seen to be a well defined function of the conductivity σ and the dielectric constant ϵ. Two alternative methods then suggest themselves as being suitable for the determination of the effective σ and ϵ of the ground at audio- or radio frequencies.

Two small loops are laid out on the ground at some distance ρ. The magnitude of the transfer impedance Z is then measured as a function of the operating frequency $\omega/2\pi$. The ratio $|Z/Z_0|$ when plotted on a base proportional to $\omega^{1/2}$ is then compared to the theoretical curves. The location of the maximum gives a direct measure of the corresponding β and b for a certain frequency $\omega/2\pi$. The conductivity σ and dielectric constant ϵ can then be easily obtained.

The other method is to choose some fixed operating frequency and vary the spacing ρ. The resulting value of $|Z/Z_0|$ should then be plotted versus ρ. Again the corresponding value of σ and ϵ can be estimated.

Additional information could be obtained by measuring the phase angle but this would require complicated instrumentation.

APPENDIX

The Field of a Circular Loop

A wire loop of radius a, carrying a uniform current I, is situated at the center of cylindrical coordinate system (ρ, ϕ, z) such that the wire is defined by the circle $\rho = a$ in the plane $z = 0$. The homogeneous ground of electrical constants σ, ϵ, μ occupies the half-space $z < -h$. The dimension h is later allowed to vanish. The air has electrical constants ϵ_0, μ_0 which are taken to be equal to those of free space.

Since there is obvious polar symmetry the field components can be written in terms of a scalar function F (Wait, 1951) as follows:

$$i\mu\omega H_\rho = \frac{\partial^2 F}{\partial\rho\partial z}, \qquad E_\phi = \frac{\partial F}{\partial\rho}, \qquad i\mu\omega H_z = -\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial F}{\partial\rho}\right) \tag{4}$$

and

$$E_\rho = H_\phi = E_z = 0.$$

At low frequencies the primary excitation F_p of the loop is represented by

$$F_p = \frac{i\mu\omega a I}{2}\int_0^\infty J_1(\lambda a) J_0(\lambda\rho) e^{-\lambda|z|}\lambda^{-1} d\lambda \tag{5}$$

where J_0 and J_1 are Bessel functions of the first type of order zero and one respectively. This result has been given in equivalent form by Slichter (1933). It can be checked by seeing that as a becomes small

$$[F_p]_{a\to 0} = \frac{i\mu\omega a^2 I}{4}\int_0^\infty J_0(\lambda\rho)e^{-\lambda|z|}d\lambda = i\mu\omega a^2 I(\rho^2+z^2)^{-1/2}/4.$$

The fields are now those of a magnetic dipole whose moment is $\pi a^2 I$. Also it can be seen that the axial magnetic field of the loop is given by

$$[H_z]_{\rho\to 0} = \frac{aI}{2}\int_0^\infty J_1(\lambda a)\lambda e^{-\lambda z|z}d\lambda = a^2 I(a^2+z^2)^{-3/2}/2,$$

which is also well known.

The general solution of the problem is of the following form:

$$F_0 = c\int_0^\infty [f_0(\lambda)e^{\lambda z} + g_0(\lambda)e^{-\lambda z}]J_0(\lambda\rho)d\lambda \quad \text{for} \quad -h \leqq z \leqq 0 \tag{6}$$

and

$$F_1 = c\int_0^\infty f_1(\lambda)e^{uz}J_0(\lambda\rho)d\lambda \quad \text{for} \quad z < -h \tag{7}$$

where

$$c = i\mu\omega aI/4, \qquad f_0(\lambda) = 2J_1(\lambda a)/\lambda a,$$

and

$$u = (\lambda^2+\gamma^2)^{1/2}.$$

The functions $g_0(\lambda)$ and $f_1(\lambda)$ are determined by the two conditions which require that the tangential field components are continuous at the boundary $z=-h$. It then easily follows that

$$g_0(\lambda) = -f_0(\lambda)e^{-\lambda h}\left[\frac{\mu_0 u - \mu\lambda}{\mu_0 u + \mu\lambda}\right]$$

and

$$f_1(\lambda) = [f_0(\lambda)e^{-\lambda h} + g_0(\lambda)e^{\lambda h}]e^{uh}.$$

The formal solution of the problem is thus specified.

The case is now considered where the loop is lying on the ground and the ground permeability is taken to be the same as the air so that for $z=0$

$$F_0 = c\int_0^\infty \frac{2\lambda}{u+\lambda} f_0(\lambda)J_0(\lambda\rho)d\lambda.$$

A well known expansion for the Bessel function $J_1(x)$ is given by

$$J_1(x) = \sum_0^\infty \frac{(-1)^m x^{2m+1}}{m!(m+1)!2^{2m+1}}$$

so that

$$F_0 = 2c \sum_0^\infty \frac{(-1)^m a^{2m}}{m!(m+1)!2^{2m}} \int_0^\infty \frac{\lambda^{2m+1}}{u+\lambda} J_0(\lambda\rho) d\lambda.$$

Introducing Sommerfeld's integral (Sommerfeld, 1949, p. 242)

$$\int_0^\infty \lambda u^{-1} J_0(\lambda\rho) e^{-u\alpha} d\lambda = \frac{e^{-\gamma(\rho^2+\alpha^2)^{1/2}}}{(\rho^2+\alpha^2)^{1/2}} = P$$

it is seen that

$$\int_0^\infty u\lambda J_0(\lambda\rho) d\lambda = \left[\frac{\partial^2 P}{\partial\alpha^2}\right]_{\alpha=0} = -\frac{1}{\rho^3}(1+\gamma\rho)e^{-\gamma\rho}. \tag{8}$$

From another well known result

$$\int_0^\infty J_0(\lambda\rho) e^{-\lambda\alpha} d\lambda = (\rho^2+\alpha^2)^{-1/2} = Q$$

it is seen that

$$\int_0^\infty \lambda^2 J_0(\lambda\rho) d\lambda = \left[\frac{\partial^2 Q}{\partial\alpha^2}\right]_{\alpha=0} = \frac{1}{\rho^3}. \tag{9}$$

Combining the results of equations (8) and (9) it follows that

$$\int_0^\infty \frac{\lambda J_0(\lambda\rho) d\lambda}{u+\lambda} = \gamma^{-2}\rho^{-3}[1-(1+\gamma\rho)e^{-\gamma\rho}] = R(\gamma\rho) \tag{10}$$

and by making use of the fact that $J_0(\lambda\rho)$ satisfies the equation

$$\left[\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial}{\partial\rho}\right) + \lambda^2\right] J_0(\lambda\rho) = 0$$

it readily follows that

$$\int_0^\infty \frac{\lambda^{2m+1} J_0(\lambda\rho)}{u+\lambda} = \left[-\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial}{\partial\rho}\right)\right]^m R(\gamma\rho). \tag{11}$$

The vertical magnetic field H_z on the earth is then given by

$$i\mu\omega H_z = -2c \sum_0^\infty \cdot \frac{(a/2)^{2m}}{m!(m+1)!}\left[\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial}{\partial\rho}\right)\right]^{m+1} R(\gamma\rho). \tag{12}$$

When the ratio a/ρ becomes small, only the first term of the series is significant and then H_z is given by

$$H_z = A_1 I(2\pi\gamma^2\rho^5)^{-1}[9 - (9 + 9\gamma\rho + 4\gamma^2\rho^2 + \gamma^3\rho^3)e^{-\gamma\rho}] \qquad (13)$$

where

$$A_1 = \pi a^2.$$

The mutual impedance Z between a loop of area A_1 and a loop of area A_2 whose dimensions are small compared to their separation ρ is then

$$Z = i\mu\omega H_z A_2/I,$$

which is identical to equation (2).

It can be readily checked that the error in neglecting the higher order terms in the series in equation (12) does not exceed 1% if the separation ρ is greater than about 5 loop diameters.

ACKNOWLEDGMENT

Considerable assistance was received from Mr. David Dickson who carried out the necessary numerical computations.

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NOTE ADDED IN PROOF:

Equation (13) for H_z can be extended to a stratified ground for the case $|\gamma\rho| \gg 1$ by the approximate formula:

$$H_z \simeq 9A_1 I(2\pi\gamma^2\rho^5)^{-1}Q^2$$

where Q, a correction factor, is defined and tabulated in a previous paper: Wait, J. R. (1953), The fields of a line source of current over a stratified conductor: Appl. Sci. Research, Sec. B, vol. 3, p. 279–292.

SUB-SURFACE ELECTRICAL MEASUREMENTS ABOUT TWO PLANE INTERFACES*

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ABSTRACT

Many response curves have been calculated for multiple-electrode logging devices passing through thin beds (Guyod, 1944, parts 5, 6, 7, 8, 9, 10, and 11). For conditions where one can assume equal resistivity material above and below the thin bed, all electrodes in a line normal to the interfaces, and bore hole effects negligible, a function $G_A(x)$ is introduced to make possible rapid computations. Tables and examples are included.

INTRODUCTION AND SUMMARY

The electrical potential distribution about a point source in the vicinity of one or more parallel plane interfaces separating two or more homogeneous isotropic materials has been solved previously by Guyod (1944, part 5), Jakosky (1950, p. 483), Smythe (1950, p. 182), and others. Surface electrical exploration is, in part, a particular case of this problem in which all electrodes are on the upper interface. Rapid calculations of surface problems may be made with the aid of methods developed by Roman or Tagg and described by Jakosky (1950, p. 488, p. 491). Subsurface electrical measurements about a thin bed with material of equal resistivity above and below and with all electrodes in a line normal to the interfaces is another particular case of this problem. The function $G_A(x)$, defined below, leads to rapid computation of sub-surface problems of this type. For a better understanding of the general problem, a brief solution is given, following the procedure used by Smythe. The problem is then limited to the case where the resistivity of the material below the thin bed is equal to that above and where the electrodes are on the z-axis. The unit of linear measure is made equal to bed thickness, and the function $G_A(x)$ is introduced. All solutions are expressed as functions of $G_A(x)$.

GENERAL PROBLEM

Consider a point current source at the origin of a cylindrical coordinate system in a material of resistivity ρ_1, a plane interface at $z=a>0$ with material ρ_2 above, and a second plane interface at $z=b>a$ with material ρ_2 below and ρ_3 above (Fig. 1). Let V_1 be the potential of a point within material ρ_1, etc. We shall write three equations for the potential of a point within the three materials. The solutions of these equations are cylindrical harmonics.

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Laplace's equation in cylindrical coordinates is:

$$\nabla^2 V = \frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} + \frac{1}{r^2}\frac{\partial^2 V}{\partial \phi^2} + \frac{\partial^2 V}{\partial z^2} = 0. \tag{1}$$

With the material symmetrical about the z-axis, the solution is independent of ϕ; one solution is

$$V = \frac{\rho I}{4\pi}\int_0^\infty [e^{-\lambda|z|} + \theta(\lambda)e^{-\lambda z} + \psi(\lambda)e^{\lambda z}]J_0(\lambda r)d\lambda \tag{2}$$

where $J_0(\lambda r)$ is a Bessel function of zero order of the first kind and $\theta(\lambda)$ and $\psi(\lambda)$ are arbitrary functions chosen to satisfy the boundary conditions. Three cylindrical harmonics are

$$V_1 = \frac{\rho_1 I}{4\pi}\int_0^\infty [e^{-\lambda|z|} + \theta_1(\lambda)e^{-\lambda z} + \psi_1(\lambda)e^{\lambda z}]J_0(\lambda r)d\lambda \tag{3}$$

$$V_2 = \frac{\rho_1 I}{4\pi}\int_0^\infty [e^{-\lambda|z|} + \theta_2(\lambda)e^{-\lambda z} + \psi_2(\lambda)e^{\lambda z}]J_0(\lambda r)d\lambda \tag{4}$$

$$V_3 = \frac{\rho_1 I}{4\pi}\int_0^\infty [e^{-\lambda|z|} + \theta_3(\lambda)e^{-\lambda z} + \psi_3(\lambda)e^{\lambda z}]J_0(\lambda r)d\lambda. \tag{5}$$

The boundary conditions on the interface $z=a$ are:

$$V_1 = V_2 \tag{6}$$

$$\rho_2\frac{\partial V_1}{\partial z} = \rho_1\frac{\partial V_2}{\partial z}. \tag{7}$$

The boundary conditions on the interface $z=b$ are:

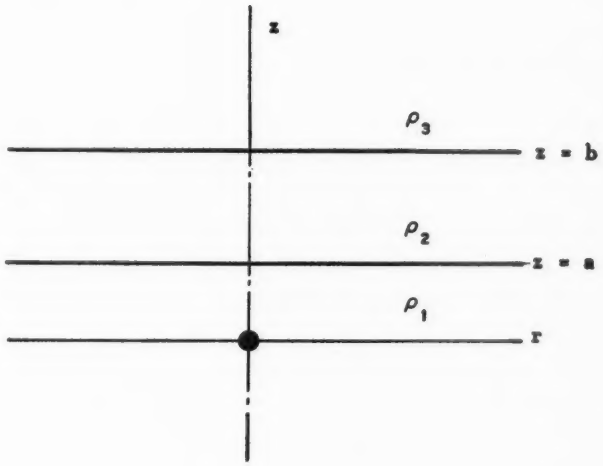
$$V_2 = V_3 \tag{8}$$

$$\rho_3\frac{\partial V_2}{\partial z} = \rho_2\frac{\partial V_3}{\partial z}. \tag{9}$$

Another boundary condition is that $V\to 0$ as $r^2+z^2\to\infty$. Application of these boundary conditions to the three cylindrical harmonics above reduces the six arbitrary functions to four and gives four equations. The four solutions are substituted into the three harmonics, and the harmonics are integrated. The results of these operations are shown in Figure 1. In Figure 2 is the solution to a similar boundary problem but with the current source between the two interfaces.

LIMITED PROBLEM

The solutions above are laborious to use because of the infinite series. In electrical well logging, if we consider the bore hole normal to the bed, we are inter-



$$A = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

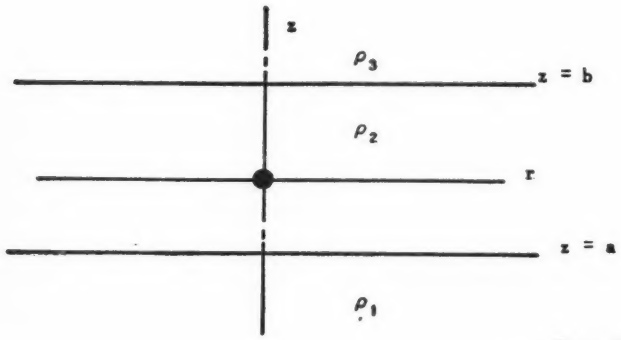
$$B = \frac{\rho_3 - \rho_2}{\rho_3 + \rho_2}$$

$$V_1 = \frac{\rho_1 I}{4\pi}\left\{ \frac{1}{(r^2 + z^2)^{\frac{1}{2}}} + \frac{A}{\left[r^2 + (2a-z)^2\right]^{\frac{1}{2}}} + (1-A^2)\sum_{n=0}^{\infty} \frac{(-1)^n A^n B^{n+1}}{\left[r^2 + [2n(b-a) + 2b-z]^2\right]^{\frac{1}{2}}} \right\}$$

$$V_2 = \frac{\rho_1 I}{4\pi}(1 + A)\left\{ \sum_{n=0}^{\infty} \frac{(-1)^n A^n B^n}{\left[r^2 + [2n(b-a) + z]^2\right]^{\frac{1}{2}}} + \sum_{n=0}^{\infty} \frac{(-1)^n A^n B^{n+1}}{\left[r^2 + [2n(b-a) + 2b-z]^2\right]^{\frac{1}{2}}} \right\}$$

$$V_3 = \frac{\rho_1 I}{4\pi}(1+A)(1+B)\sum_{n=0}^{\infty} \frac{(-1)^n A^n B^n}{\left[r^2 + [2n(b-a) + z]^2\right]^{\frac{1}{2}}}$$

FIG. 1. Thin bed with current electrode outside.



$$A = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

$$B = \frac{\rho_3 - \rho_2}{\rho_3 + \rho_2}$$

$$V_1 = \frac{\rho_2 I}{4\pi}\,(1-A)\left\{\sum_{n=0}^{\infty}\frac{(-1)^n A^n B^n}{\left[r^2 + [2n(b-a) - z]^2\right]^{\frac{1}{2}}} + \sum_{n=0}^{\infty}\frac{(-1)^n A^n B^{n+1}}{\left[r^2 + [2n(b-a) + 2b - z]^2\right]^{\frac{1}{2}}}\right\}$$

$$V_2 = \frac{\rho_2 I}{4\pi}\left\{\frac{1}{(r^2+z^2)^{\frac{1}{2}}} + \sum_{n=0}^{\infty}\frac{(-1)^{n+1} A^{n+1} B^n}{\left[r^2+[2n(b-a)-2a+z]^2\right]^{\frac{1}{2}}} + \sum_{n=1}^{\infty}\frac{(-1)^n A^n B^n}{\left[r^2+[2n(b-a) + z]^2\right]^{\frac{1}{2}}} + \sum_{n=0}^{\infty}\frac{(-1)^n A^n B^{n+1}}{\left[r^2+[2n(b-a)+2b-z]^2\right]^{\frac{1}{2}}} + \sum_{n=1}^{\infty}\frac{(-1)^n A^n B^n}{\left[r^2+[2n(b-a) - z]^2\right]^{\frac{1}{2}}}\right\}$$

$$V_3 = \frac{\rho_2 I}{4\pi}\,(1+B)\left\{\sum_{n=0}^{\infty}\frac{(-1)^n A^n B^n}{\left[r^2 +[2n(b-a) + z]^2\right]^{\frac{1}{2}}} + \sum_{n=0}^{\infty}\frac{(-1)^{n+1} A^{n+1} B^n}{\left[r^2 + [2n(b-a)-2a+z]^2\right]^{\frac{1}{2}}}\right\}$$

FIG. 2. Thin bed with current electrode inside.

ested only in points on the z-axis. Let $r=0$ and rewrite the first series to appear in Figure 1 as

$$\sum_{n=0}^{\infty} \frac{(-1)^n A^n B^{n+1}}{2n(b-a)+2b-z}. \tag{10}$$

Often in well logging, we are concerned with a thin bed with a like formation above and below. Let $\rho_3=\rho_1$, therefore $B=-A$. Substituting in the above series;

$$\sum_{n=0}^{\infty} \frac{(-1)^n A^n (-A)^{n+1}}{2n(b-a)+2b-z} = -A\sum_{n=0}^{\infty} \frac{A^{2n}}{2n(b-a)+2b-z}. \tag{11}$$

For the equations to be homogeneous, only one unit of linear measure can be used. If ohm-meters is used for unit volume resistivity, all linear measurements must be made in meters. If ohm-feet is used, all linear measurements must be made in feet. Here, the most convenient linear measure is bed-thickness, with volume resistivity in ohm-bed thicknesses. Let the bed thickness be one unit; therefore, $b=a+1$. Substituting in the above series, we obtain

$$-A\sum_{n=0}^{\infty} \frac{A^{2n}}{2(a+1)-z+2n}. \tag{12}$$

The $n=0$ term does not appear in all the series. Let us rewrite this in the form:

$$-\frac{A}{2(a+1)-z} - A\sum_{n=1}^{\infty} \frac{A^{2n}}{2(a+1)-z+2n}. \tag{13}$$

We define

$$G_A(x) = \sum_{n=1}^{\infty} \frac{A^{2n}}{x+2n}. \tag{14}$$

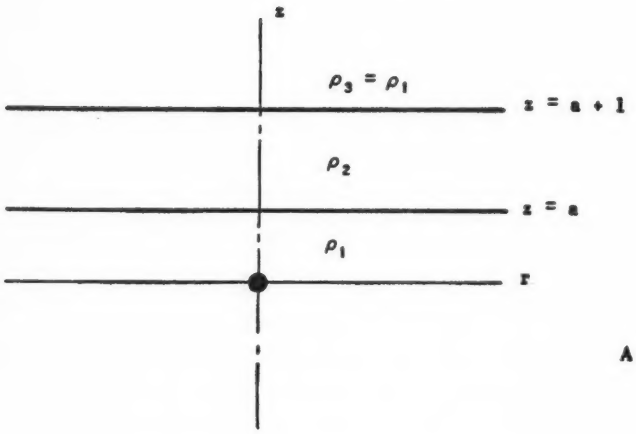
With this notation and the above limitations, the original series is:

$$-\frac{A}{2(a+1)-z} - AG_A[2(a+1)-z]. \tag{15}$$

In a like manner, all the series appearing in the solution to the original problems may be written as a function of $G_A(x)$. The solutions are rewritten as a function of $G_A(x)$ in Figures 3 and 4. The function $G_A(x)$ is plotted in Figure 5 and tabulated in the tables.

TABLES

In computing the tables, the function was expanded from eight terms for $A=0.3333$ to a maximum of 2,600 terms for $A=0.9980$. Third order interpolation was used to get many of the points in the table. The computing was done with the aid of electronic computing machines by the Tabulating Section of Halliburton



$$A = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

$$V_1 = \frac{\rho_1 I}{4\pi}\left\{\frac{1}{|z|} + \frac{A}{2a - z} - \frac{(1-A^2)A}{2(a+1) - z} - (1-A^2)AG_A\left[2(a+1)-z\right]\right\}$$

$$V_2 = \frac{\rho_1 I}{4\pi}(1+A)\left\{\frac{1}{z} + G_A(z) - \frac{A}{2(a+1)-z} - AG_A\left[2(a+1) - z\right]\right\}$$

$$V_3 = \frac{\rho_1 I}{4\pi}(1-A^2)\left\{\frac{1}{z} + G_A(z)\right\}$$

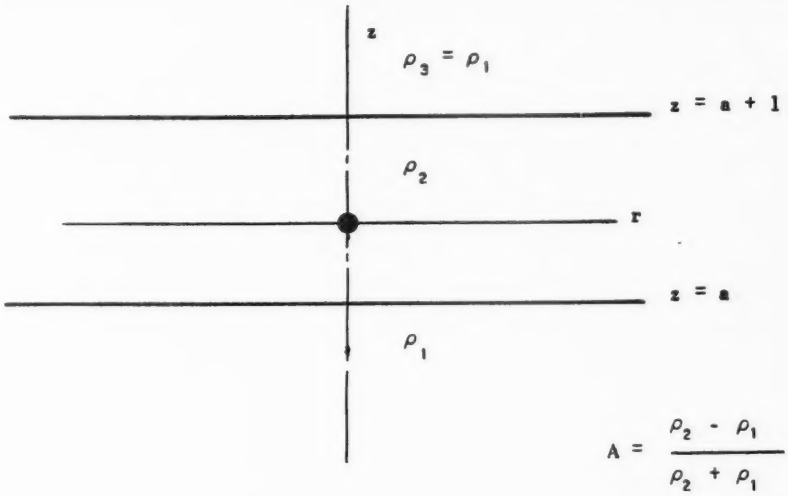
FIG. 3. Thin bed with current electrode outside. Potential of any point on z-axis expressed in terms of function $G_A(x)$.

Oil Well Cementing Company. We believe the tables to be correct to within $\pm .0001$. The complete tables are available for inspection at the Halliburton Oil Well Cementing Company's Laboratories, 1628 Old Spanish Trail, Houston, Texas.

EXAMPLE FOR A TWO-ELECTRODE LOGGING DEVICE

In Figure 6 is pictured a 2Z18-inch logging device with the midpoint, or depth reference, 0.2 ft below the lower interface of a 7.5-ft bed of 18 ohm-meter material. Material of 1.8 ohm-meter resistivity is above and below the bed. The problem is to calculate the apparent resistivity that the device will indicate.

Most logging devices are calibrated to read true resistivity when in a homogeneous material. It can be shown that the recorded apparent resistivity of a two-electrode device is:



$$V_1 = \frac{\rho_2 I}{4\pi}(1-A)\left\{\frac{1}{(-z)} + G_A(-z) - \frac{A}{2(a+1)-z} - AG_A\left[2(a+1)-z\right]\right\}$$

$$V_2 = \frac{\rho_2 I}{4\pi}\left\{\frac{1}{|z|} - \frac{A}{z-2a} - AG_A(z-2a) + G_A(z) - \frac{A}{2(a+1)-z} - AG_A\left[2(a+1)-z\right] + G_A(-z)\right\}$$

$$V_3 = \frac{\rho_2 I}{4\pi}(1-A)\left\{\frac{1}{z} + G_A(z) - \frac{A}{z-2a} - AG_A(z-2a)\right\}$$

FIG. 4. Thin bed with current electrode inside. Potential of any point on z-axis expressed in terms of $G_A(x)$.

$$\rho_a = \frac{4\pi s}{I} V_{P_1}. \tag{16}$$

This reduces the problem to one of finding V_{P_1} or the potential of the pickup electrode. We have taken the lower electrode as the current electrode; we have the condition in Figure 3 and will use that set of equations. Converting the linear measurements to units of bed thicknesses:

$$s = 1.5\,\text{ft}\left(\frac{\text{bt}}{7.5\,\text{ft}}\right) = .2\ \text{bt}$$

$$z = s = .2\ \text{bt}$$

$$a = .95\,\text{ft}\left(\frac{\text{bt}}{7.5\,\text{ft}}\right) = .127\ \text{bt}.$$

Let

$$I = 4\pi \text{ amps}.$$

The contrast between the beds is 10 to 1; let

$$\rho_1 = 1 \text{ ohm-bt},$$

$$\rho_2 = 10 \text{ ohm-bt},$$

$$A = .8182$$

and later multiply the answer by 1.8 ohm-meters/ohm-bt to get apparent resistivity in ohm-meters.

The pickup electrode is in material ρ_2; using the equation for V_2 of Fig. 3,

$$V_{P_1} = \frac{\rho_1 I}{4\pi}(1 + A)\left\{\frac{1}{z} + G_A(z) - \frac{A}{2(a+1) - z} - AG_A[2(a+1) - z]\right\}$$

$$= 1.8182\left\{\frac{1}{.2} + G_{.8182}(.2) - \frac{.8182}{2(1.127) - .2} - .8182G_{.8182}[2(1.127) - .2]\right\}. \qquad (17)$$

Rewriting with values from the tables,

$$V_{P_1} = 1.8182\{5 + .5150 - .3983 - .8182(.3235)\} = 8.822 \text{ volts},$$

and substituting into equation (16),

$$\rho_a = (.2)(8.822) = 1.764 \text{ ohm-bt}.$$

Multiplying by 1.8,

$$\rho_a = (1.764)(1.8) = 3.18 \text{ ohm-meters}.$$

In Figure 7 is a log, typical of what may be seen on a field log, that was made up by plotting this and other similar computed points.

EXAMPLE FOR A 3-ELECTRODE LOGGING DEVICE

In Figure 8 is pictured a 3iZ16-ft logging device with the depth reference the mid-point between P_1 and P_2, 1.5 feet above the lower interface of a 40-ft bed of

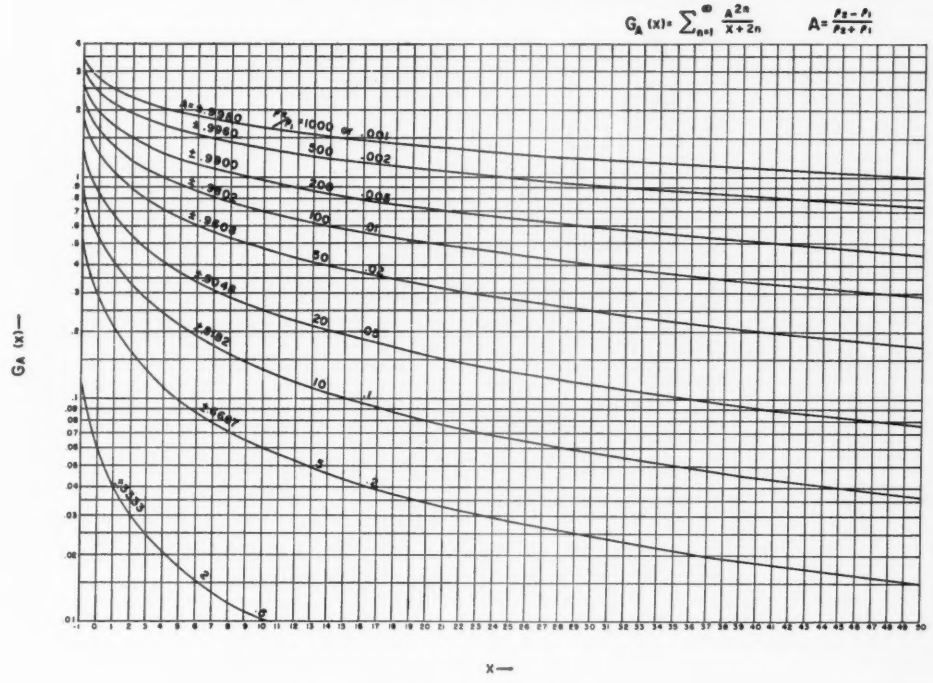


FIG. 5. $G_A(x)$ as a function of x.

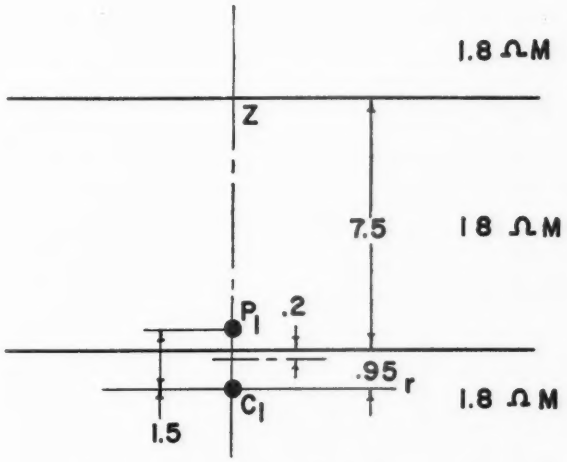


FIG. 6. 2Z18-inch logging device in 7½-foot bed.

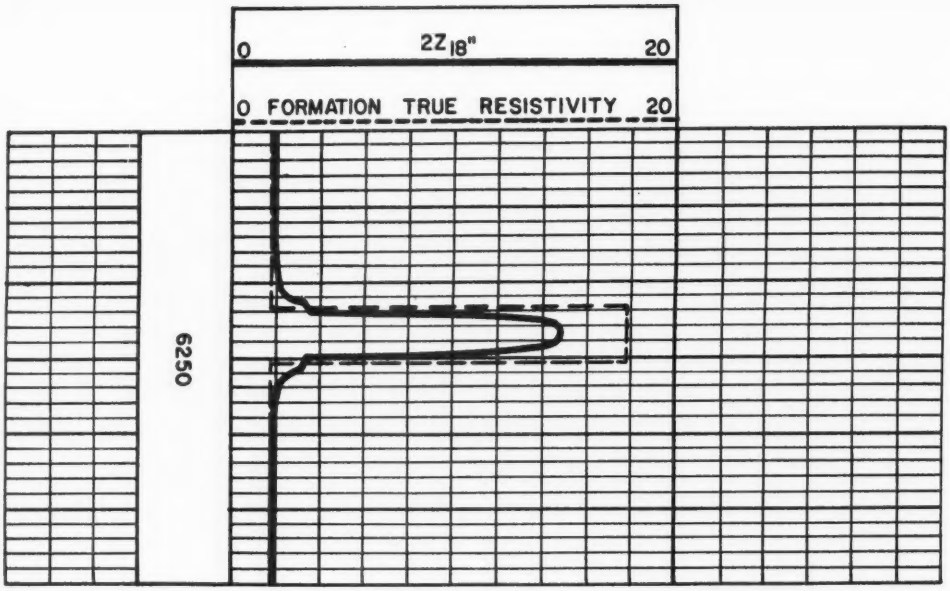


FIG. 7. 2Z18-inch log through a 7½-foot bed of 18 ohm-meter material with 1.8 ohm-meter material above and below. Borehole effect neglected.

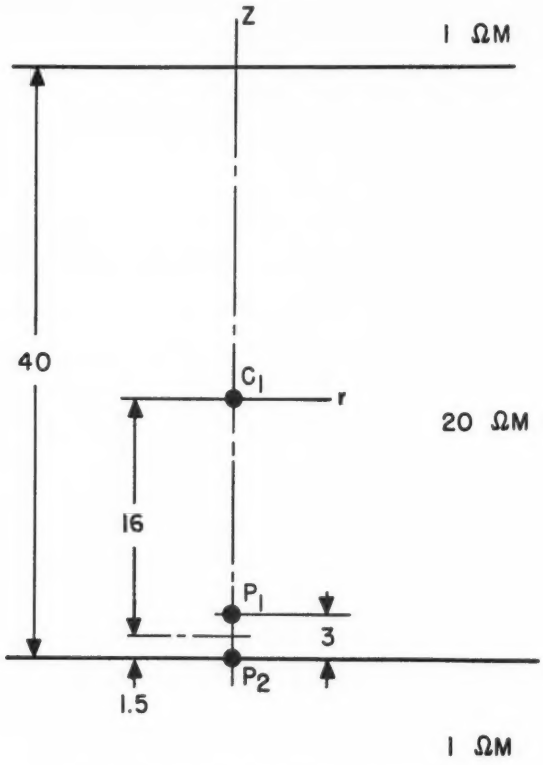


FIG. 8. 3iZ16-ft logging device in 40-foot bed.

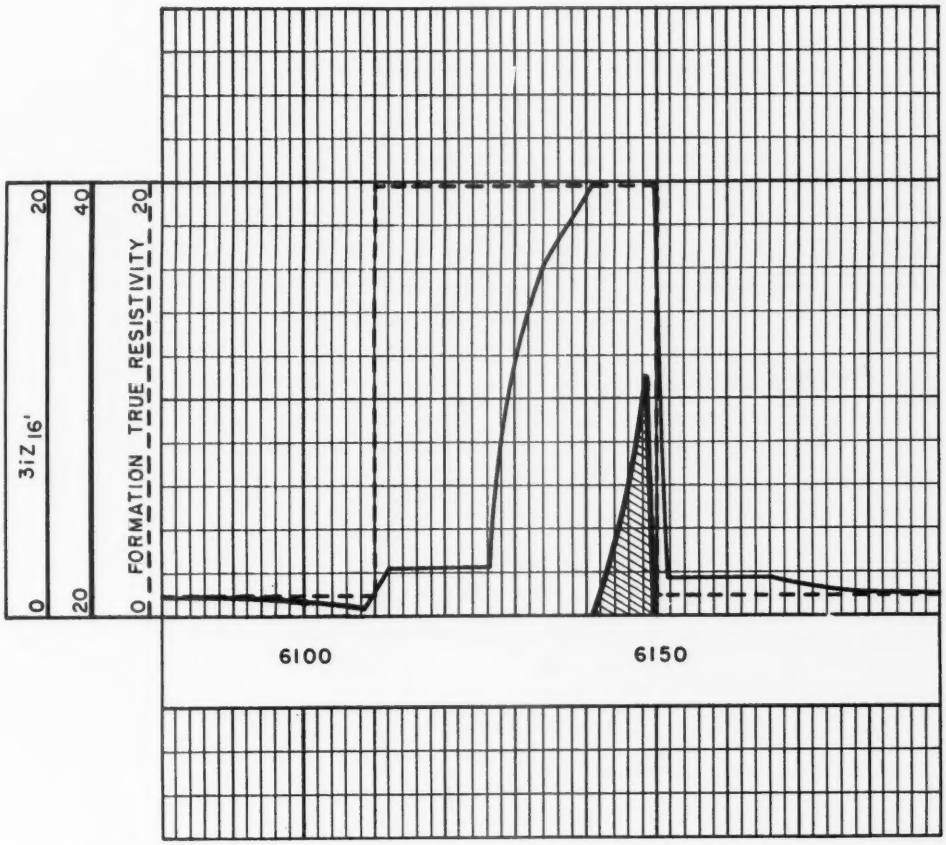


FIG. 9. $3iZ_{16}$-ft log through a 40-foot bed of 20 ohm-meter material with 1 ohm-meter material above and below. Borehole effect neglected.

20 ohm-meter material. One ohm-meter material is above and below the bed. The problem is to calculate the apparent resistivity that the device indicates. The response of the device is

$$\rho_a = \frac{4\pi}{I\left[\frac{1}{\overline{C_1P_1}} - \frac{1}{\overline{C_1P_2}}\right]}(V_{P_1} - V_{P_2}). \tag{18}$$

The parameters are:

$$\overline{C_1P_1} = 14.5 \text{ ft}\left(\frac{\text{bt}}{40 \text{ ft}}\right) = .3625 \text{ bt},$$

$$\overline{C_1P_2} = 17.5 \text{ ft}\left(\frac{\text{bt.}}{40 \text{ ft}}\right) = .4375 \text{ bt},$$

$$z_{P_1} = -\overline{C_1P_1} = -.3625 \text{ bt},$$

$$z_{P_2} = -\overline{C_1P_2} = -.4375 \text{ bt},$$

$$a = -17.5 \text{ ft}\left(\frac{\text{bt}}{40 \text{ ft}}\right) = -.4375 \text{ bt},$$

$$I = 4\pi$$

$$\rho_1 = 1$$

$$\rho_2 = 20$$

$$A = .9048.$$

Substituting into equation (18),

$$\rho_a = \frac{1}{\frac{1}{.3625} - \frac{1}{.4375}}(V_{P_1} - V_{P_2}) = 2.1146(V_{P_1} - V_{P_2}). \tag{19}$$

Both P_1 and C_1 electrodes are inside material ρ_2; for V_{P_1} we shall use the equation for V_2 of Figure 4.

$$V_{P_1} = \frac{\rho_2 I}{4\pi}\left\{\frac{1}{|z|} - \frac{A}{z-2a} - AG_A(z-2a) + G_A(z) - \frac{A}{2(a+1)-z} - AG_A[2(a+1)-z] + G_A(-z)\right\}$$

$$= 20\left\{\frac{1}{.3625} - \frac{.9048}{-.3625+2(.4375)} - .9048\,G_{.9048}[-.3625+2(.4375)] + G_{.9048}(-.3625) - \frac{.9048}{2(-.4375+1)+.3625} - .9048\,G_{.9048}[2(-.4375+1)+.3625] + G_{.9048}(.3625)\right\} = 18.23. \tag{20}$$

Electrode P_2 is on the interface. Equations for either V_1 or V_2 may be used. We shall use the equation for V_1 of Figure 4 since it is shorter.

$$V_{P_2} = \frac{\rho_2 I}{4\pi}(1-A)\left\{\frac{1}{(-z)} + G_A(-z) - \frac{A}{2(a+1)-z} - AG_A[2(a+1)-z]\right\}$$

$$= 20(1-.9048)\left\{\frac{1}{.4375} + G_{.9048}(.4375) - \frac{.9048}{2(-.4375+1)+.4375} - .9048\,G_{.9048}[2(-.4375+1)+.4375]\right\} = 3.65. \tag{21}$$

Substituting into equation (19),

$$\rho_a = 2.1146(18.23 - 3.65)$$
$$= 30.8 \text{ ohm-meters.}$$

In Figure 9 is a plotted log of this and other similar computed points.

CONCLUSIONS

In using the function $G_A(x)$, the only extra work required is that of converting linear dimensions to units of bed thickness. This is very little labor compared to that of expanding the series. The restrictions are:

1. The potential point is on the z-axis, i.e. $r=0$.
2. The material above and below the bed is of the same resistivity, i.e. $\rho_3=\rho_1$.

The tables are computed for values $-1 \leqq x \leqq 62$, which covers all spacings up to 20 bed-thicknesses and current electrode positions up to 20 bed-thicknesses from the bed. The values of A were chosen to make ρ_2/ρ_1 a round number that varies between .001 and 1,000. A is negative when $\rho_2 < \rho_1$. Use of the function $G_A(x)$ makes possible a rapid solution to this potential problem.

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MICROLATEROLOG VERSUS MICROLOG FOR FORMATION FACTOR CALCULATIONS*

HAROLD D. SMITH† AND HAROLD A. BLUM†

ABSTRACT

A comparison of the MicroLaterolog‡ and MicroLog‡ for determining formation resistivity factors indicates that the MicroLaterolog is significantly more accurate. Data supporting this conclusion are presented comparing measured formation resistivity factors from cores with calculated values from the MicroLaterolog and MicroLog in both hard- and soft-rock country. The use of the MicroLaterolog for quantitative electric log interpretation will increase the value of electric logging as an exploration tool.

INTRODUCTION

The exploratory phase of oil production does not necessarily end with the location of the wildcat drilling site but rather when the wildcat well has been drilled and proved conclusively to be productive or dry. There have been cases in the past of an operator drilling through an oil reservoir, logging the well, and plugging it without testing or making a decisive test of the zone which was later proven to be productive. The development of quantitative electric log interpretation techniques during the past several years has provided a valuable exploration tool for the oil industry. The electric log is not only useful for formation correlations but also provides the resistivity data which permit quantitative calculations of the water and oil content of the zones penetrated by the borehole.

Extensive experimental data have shown that the water saturation of a formation can be expressed quantitatively by the equation formulated by Archie (1942),

$$S^n = \frac{FR_w}{R_t} \tag{1}$$

where:

S = the water saturation (fraction of the pore space which contains water),
n = the saturation exponent,
R_t = the true formation resistivity,
R_w = formation water resistivity and
F = formation resistivity factor.

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‡ The MicroLaterolog and MicroLog are services offered by the Schlumberger Well Surveying Corporation.

Porous beds are assumed to be completely saturated either with water or a combination of oil and water, so that the fraction of the pore space (H) which contains oil will be given by:

$$H = 1.0 - S. \tag{2}$$

Equation (1) indicates that the calculated water saturation depends on the reliable determination of four factors: n, R_w, R_t, and F. The saturation exponent, n, has been found to be fairly constant and a value of 1.8 or 2.0 is generally used (Dunlap et al., 1949). Water resistivities have been measured for many formations over wide areas. These water data can often be used to estimate water resistivity values in areas where water samples are not available. The true formation resistivity can be determined, with appropriate corrections, from the apparent resistivity curves on the electric log. The formation resistivity factor, F, may be measured on formation samples in the laboratory, estimated from porosity, or may be determined from data provided by recently developed logging devices (Doll et al., 1952; Doll, 1953). An evaluation of the last method is the subject of this paper.

The formation resistivity factor is defined as the ratio of the true resistivity of the formation completely saturated with water to the resistivity of the water. This definition is derived from equation (1), for if the formation is fully saturated with water, the water saturation is equal to one and the equation becomes:

$$F = \frac{R_t}{R_w} = \frac{R_0}{R_w} \tag{3}$$

where

R_0 = the resistivity of the formation fully saturated with water.

Formation factor measurements are obtained in the laboratory by first saturating the formation samples with water; second, measuring the resistivity of the sample and the resistivity of the water; and third, calculating F from equation (3). This ratio of R_0/R_w is a constant regardless of the water resistivity for clean sands (no clay or shaly material). The formation factor is a function of water resistivity when the sands are shaly. This behavior is attributed by some investigators to adsorbed ions on the clay surface (Winsauer et al., 1953) which makes the samples containing clay appear to be conductive when saturated with high-resistivity waters.

To obtain measured formation factor data from cores (usually only a small per cent of the formations penetrated are cored) generally takes considerable time. In many cases this means that the well may have been completed or plugged before the data becomes available. For this reason a logging device which would provide formation factor data at the well site for all formations penetrated would be much superior.

The use of both the MicroLog and MicroLaterolog for determining formation factors has been discussed in two papers (Doll et al., 1952; Doll, 1953). Both of

these devices attempt to measure R_{i0}, the invaded zone resistivity. If this can be determined, then the formation factor can be obtained by dividing R_{i0} by R_{mf}, the mud filtrate resistivity. The formation factor equation, equation (3), becomes:

$$F = \frac{R_{i0}}{R_{mf}}. \tag{4}$$

The invaded zone resistivity is obtained by correcting apparent resistivities from the logs by means of interpretation charts (Doll, 1953 and Schlumberger Document 5, 1952). In an oil formation the invaded zone contains residual oil which increases the value of R_{i0}. In this case the calculated formation factor is greater than the true value and must be corrected.

The mud filtrate resistivity can either be measured on a mud sample or an approximate value can be determined from tables (Schlumberger Document 5, 1952) by knowing the mud resistivity and the formation temperature. The apparent resistivities recorded by both the MicroLaterolog and MicroLog reflect the mud cake and invaded zone resistivities. The MicroLaterolog, because of its design, is less affected by the mud cake resistivity and in many cases (such as thin mud cake) this effect is negligible.

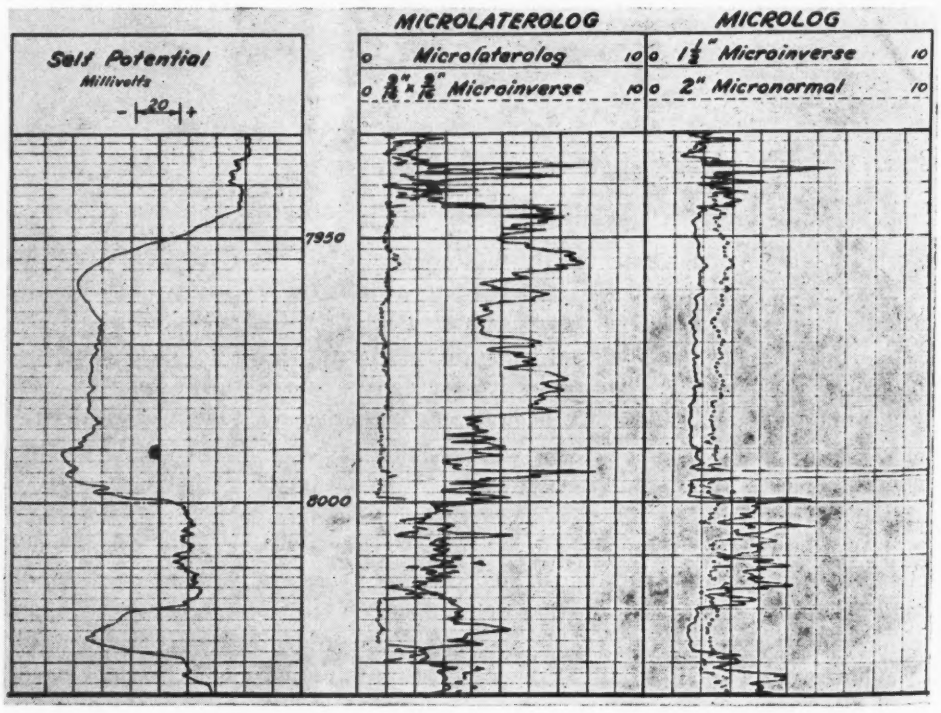

FIG. 1. Comparison of the MicroLaterolog with 9/16 in. × 9/16 in. Microinverse and MicroLog run through the same zone in the same well.

Figure 1 illustrates the comparison between the MicroLaterolog with 9/16 inch×9/16 inch Microinverse and MicroLog curves run in the same zone in the same well.

SCOPE OF INVESTIGATION

Comparisons were made between formation factors measured on cores and calculated from logs in both sandstone and limestone formations. For the evaluation in sandstone formations, the formation factor data from three MicroLaterologs were compared with the core measurements. In two of these cases the MicroLog was also run. This provided a direct comparison between the MicroLaterolog and the MicroLog. Measured and calculated data for two zones where only the MicroLog was run are also included.

In limestone formations, the formation factor data from five MicroLaterologs (six zones) were compared with the core measurements. MicroLogs were run on three of these.

In addition to the comparison between measured and calculated data on clean sands, a study was also made in a shaly sand.

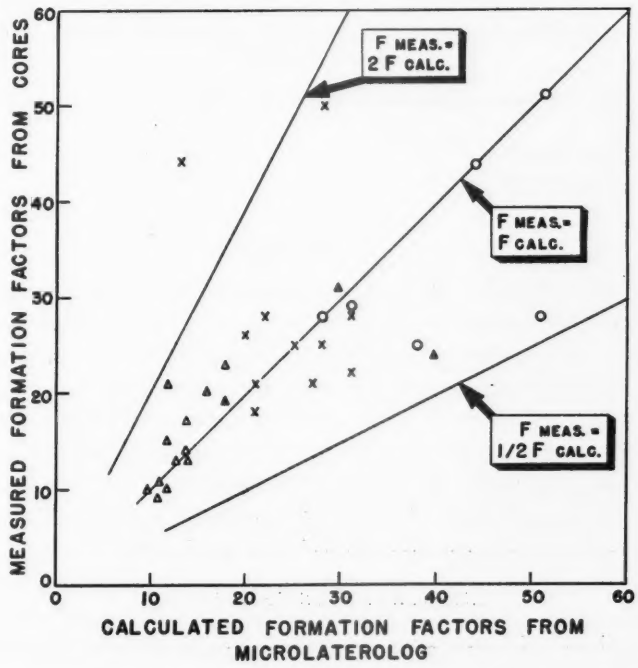

FIG. 2. Comparison between measured and calculated formation factors from the MicroLaterolog in sandstones.

△—Marginulina (Olig.)
○—Springer (Penn.)
×—Canyon (Penn.)

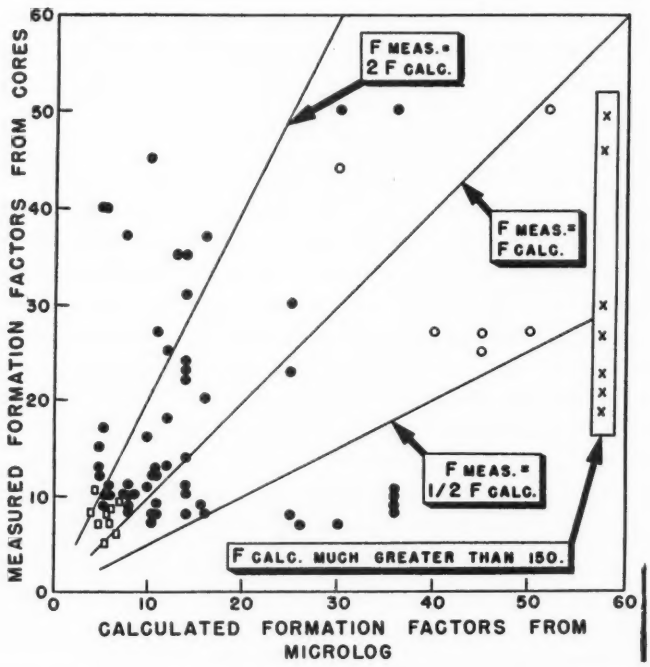

FIG. 3. Comparison between measured and calculated formation factors from the MicroLog in sandstones.

○—Springer (Penn.)
×—Canyon (Penn.)
●—Wilcox (Eocene)
□—Jackson (Eocene)

PROCEDURE

Formation factors were measured on plugs from diamond cores or on sidewall cores. The core depths were shifted in some cases to adjust for differences in drillers and logging depths. Calculated formation factors were obtained by using the recommended methods discussed in the introduction.

Formation factors on shaly sand cores were measured with a water having approximately the same resistivity as the formation water and with a water having approximately the same resistivity as the mud filtrate. This was done to determine the effect of the mud filtrate, when fresher than the formation water, on measured and calculated formation factors in shaly sands.

INTERPRETATION OF RESULTS

Figure 2 is a plot of measured formation factors as a function of calculated values from the MicroLaterolog for sandstones. The range of formation factors are from 10 to 60 with an average deviation of 1.30 for the three formations shown on the graph. The deviations were calculated by dividing the larger F by the smaller F for a given core regardless of whether the larger was the calculated or

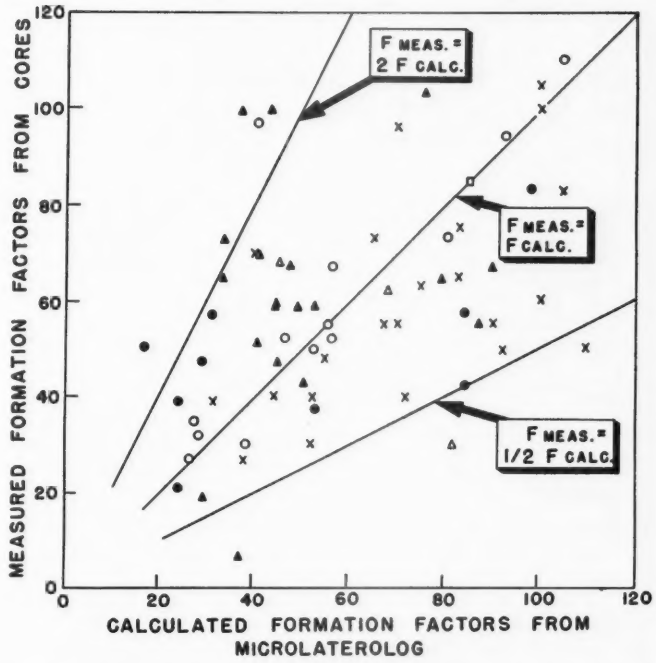

FIG. 4. Comparison between measured and calculated formation factors from the MicroLaterolog in limestones.

○—Cotton Valley (Jur.)
×—Ellenburger (Ord.)
●—Canyon (Penn.)
□—Maquoketa Dolomite (Ord.)
△—Lansing (Penn.)
▲—Strawn (Penn.)

measured value. This means that the calculated value can be, on an average, 1.30 times less than or greater than the measured value. The MicroLaterolog with the simultaneous 9/16 inch×9/16 inch Microinverse was run in the Marginulina formations and the data in this case indicate an average deviation of 1.23. The agreement between measured and calculated data for these three sands is generally good.

The comparison with MicroLog derived formation factors, shown in Figure 3, is not nearly so good. Two of these cores, from the Springer and the Canyon sands, cover the same intervals for both devices. The average deviation in the Springer was 1.5 while the calculated values in the Canyon were very much greater (as much as ten times) than the measured values. The comparison presented in Figure 3 for the Wilcox and Jackson sands (only the MicroLog was run here) is not good. The average deviation for the Wilcox was 2.2 and 1.5 for the Jackson sand.

Figures 4 and 5, for limestone, compare measured with calculated data for the two devices in the case of formation factors from about 20 to 120. In Figures 6 and 7, the complete range ($F = 20$ to 700) is presented. The overall average de-

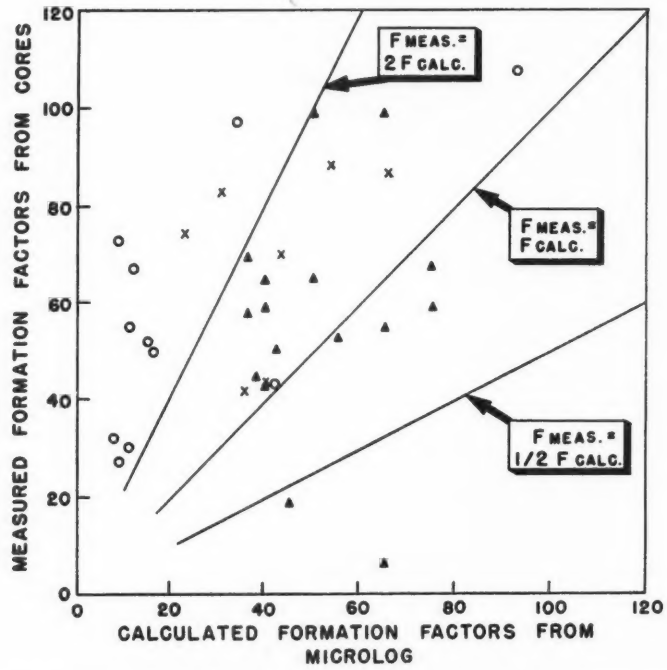

FIG. 5. Comparison between measured and calculated formation factors from the MicroLog in limestones.

○—Cotton Valley (Jur.) ▲—Strawn (Penn.)
×—Ellenburger (Ord.)

viation between measured and calculated values for the MicroLaterolog is 1.42 with exception of the Strawn, which is 2.77. The reason for the unusual deviation in this case is not known. The fact that the average deviation is greater in limestone than in sandstone is in part attributed to the heterogeneity of limestone sections. It is probable that a limestone core plug may be very much different from the section sampled by the MicroLaterolog or MicroLog devices. Including the Strawn case, the MicroLaterolog shows an average deviation of 1.64 as compared to the MicroLog whose deviations ranged from approximately 2.0 to greater than 10 (Figs. 6 and 7).

Figures 8 and 9 represent the case of a shaly sand. When the formation factors are measured using a water with the same resistivity as formation water (approximately 0.086 ohm-meters at 68°F.) the calculated values are less than the measured values, for both the MicroLaterolog and the MicroLog. This behavior is expected since the micrologging devices record the resistivity of the mud filtrate invaded zone, which contains relatively fresh water. This resistivity is lower than in a clean sand because of the adsorbed ions on the clay surfaces; therefore, the calculated formation factor will be lower. When a water with the same resistivity as the mud filtrate is used in measuring the formation factors (approximately

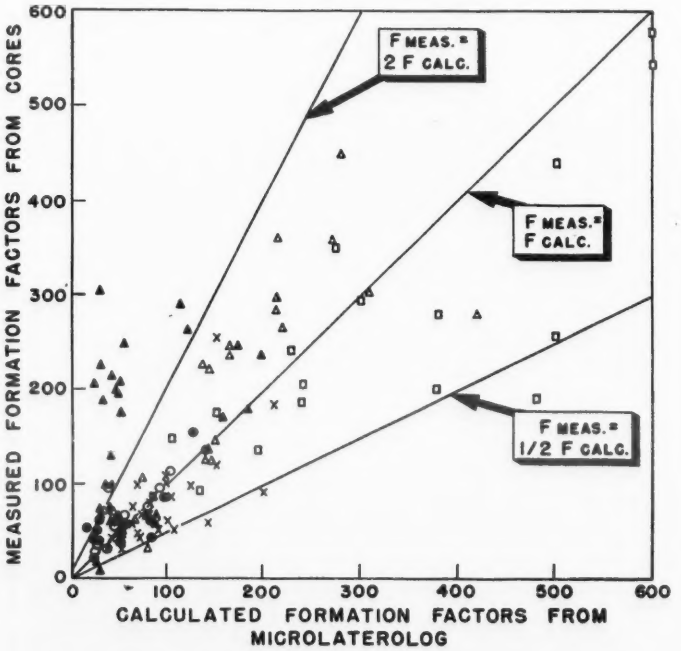

FIG. 6. Comparison between measured and calculated formation factors from the MicroLaterolog in limestones.

○—Cotton Valley (Jur.)
×—Ellenburger (Ord.)
●—Canyon (Penn.)
■—Maquoketa Dolomite (Ord.)
△—Lansing (Penn.)
▲—Strawn (Penn.)

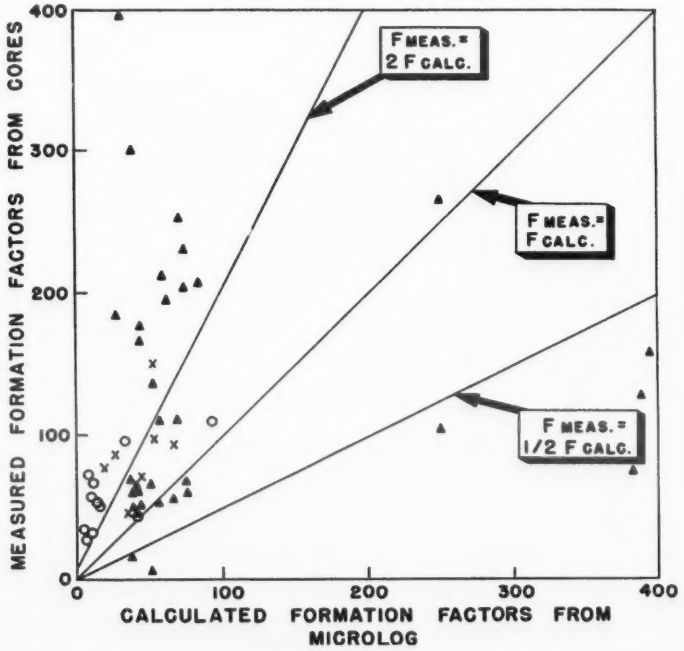

FIG. 7. Comparison between measured and calculated formation factors from the MicroLog in limestones.

○—Cotton Valley (Jur.)
×—Ellenburger (Ord.)
▲—Strawn (Penn.)

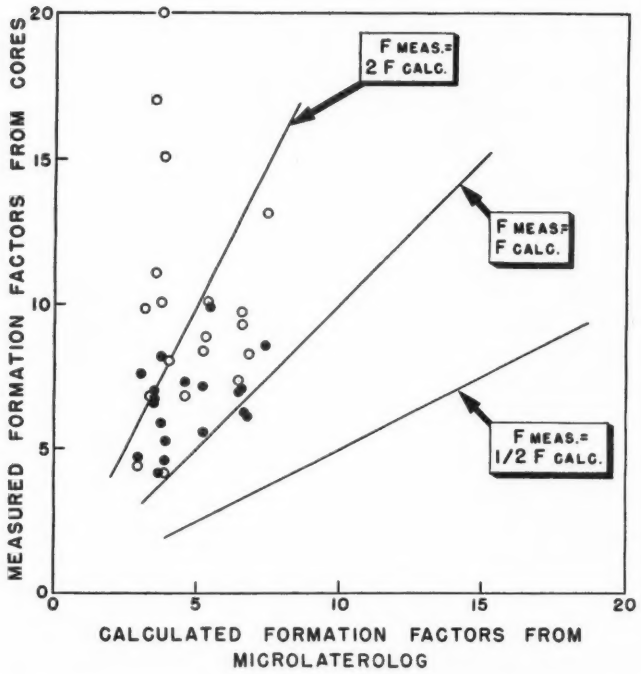

FIG. 8. Comparison between measured and calculated formation factors from the MicroLaterolog in shaly sands (Miocene).

●—Measured with a water resistivity of 0.926 ohm-meters at 68°F (approximately equal to the mud resistivity).

○—Measured with a water resistivity of 0.086 ohm-meters at 68°F (approximately equal to the formation water resistivity).

TABLE I

EFFECT OF FORMATION FACTOR DEVIATIONS ON HYDROCARBON SATURATION CALCULATIONS

	Calculated Hydrocarbon Saturation Range, per cent	
	Sandstone	Limestone
Oil Zone (80% Hydrocarbons)		
MicroLaterolog[1]	77–83	74–85
MicroLog[2]	67–88	67–88
Border Line Case (50% Hydrocarbons)		
MicroLaterolog	42–57	34–62
MicroLog	27–70	27–70
Water Zone (20% Hydrocarbons)		
MicroLaterolog	7–31	0–40
MicroLog	0–52	0–52

[1] Average deviations used were 1.3 for sandstone and 1.64 for limestone.

[2] Average deviations for the MicroLog ranged from 1.5 to >10. For this table, 2.5 was used for both the limestone and sandstone cases.

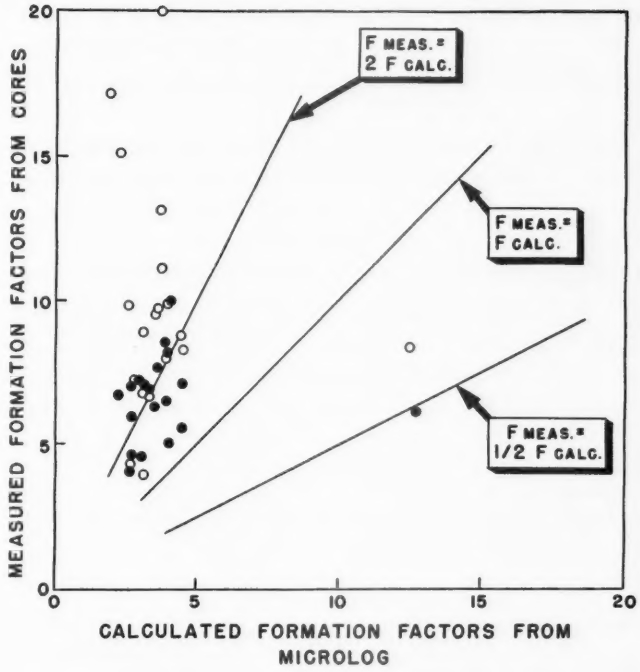

FIG. 9. Comparison between measured and calculated formation factors from the MicroLog in shaly sands (Miocene).

●—Measured with a water resistivity of 0.926 ohm-meters at 68°F (approximately equal to the mud resistivity).

○—Measured with a water resistivity of 0.086 ohm-meters at 68°F (approximately equal to the formation water resistivity).

0.96 ohm-meters at 68°F in this case), the agreement is much better between the measured and calculated data for both devices. The use of a low resistivity mud when drilling in shaly sand would make the adsorbed ion effect negligible and would result in a more representative formation factor value. The average deviation for data calculated from the MicroLaterolog is 1.36, while the average deviation is 1.85 from the MicroLog when compared to the formation factors measured in a brine of 0.96 ohm-meters. Here again, the MicroLaterolog provides more reliable data than does the MicroLog.

To better understand the significance of the reported deviations of calculated from measured formation factors, Table I has been prepared. This shows the range of calculated hydrocarbon saturations resulting from the average formation factor deviations for sandstone and limestone. It can be seen from Table I that in spite of the deviations the calculated oil saturations based on MicroLaterolog formation factor data still indicate oil and water zones. For the border line case (50% saturation) the deviations do not appreciably change the interpretation of the calculated hydrocarbon saturations for sandstone formations. The interpre-

tation of the border line case for limestone is more difficult. It is believed, however that the calculated formation factors may be more representative of limestone formations than core plugs because the MicroLaterolog averages a larger volume of rock.

It can be seen from Table I that MicroLog calculated formation factors cannot be applied very reliably to calculations of hydrocarbon saturation.

CONCLUSIONS

It is believed that the development of the MicroLaterolog has been an important advance in the art of well logging and should be particularly useful in interpreting logs of exploratory wells. From the data presented, this study has shown that (1) the MicroLaterolog can be reliably used for formation factor determinations over a wide range and (2) it is superior to the MicroLog in all cases investigated.

ACKNOWLEDGEMENT

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PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2,657,380. C. A. Donaldson. Iss. 10/27/53. App. 1/9/50.

Underground Prospecting System. An electromagnetic prospecting system in which a fractional microsecond pulse is transmitted into the ground by a pulser connected to electrode plates and picked up by similar plates some distance away and observed on a c-r tube whose sweep is triggered in synchronism with the transmitted pulse.

U. S. No. 2,659,882. W. M. Barrett. Iss. 11/17/53. App. 12/3/47.

Method of Prospecting With Timed Electric Energy. A method of radio-wave prospecting in which a high-frequency pulse is transmitted along the earth's surface so that part of the wave is refracted downward and then reflected upward by an underlying layer and the arrival of the direct and reflected pulses at the receiver are observed.

U. S. No. 2,661,466. W. M. Barrett. Iss. 12/1/53. App. 4/19/43 and 3/26/45. Assign. Engineering Research Corp.

Transmitting and Receiving Apparatus and Method for Electromagnetic Prospecting. An antenna system for use in radio-wave prospecting having an array of odd-multiple quarter-wave radiators in or below the air-earth interface.

U. S. No. 2,663,004. H. O. Seigel. Iss. 12/15/53. App. 3/15/52. Assign. Newmont Mining Corp.

Method for Determining the Size of a Subsurface Ore Body. An electric logging method for determining the transverse extent of an ore body intersected by a drill hole in which a current electrode is place in the hole on one side of the ore body and a potential electrode is placed equidistant on the other side of the ore body and the variation in apparent resistivity observed as the spacing is increased.

GRAVIMETRIC PROSPECTING

U. S. No. 2,657,581. C. H. Fay and R. R. Goodell. Iss. 11/3/53. App. 7/24/50. Assign. Shell Development Co.

Gravity Meter. A borehole gravimeter having a mass suspended on a wire which is kept in transverse oscillation by an electrostatic pick-up feeding back into an electromagnetic driver, a high mode of oscillation being used and controlled with avc and the frequency of oscillation observed at the surface.

U. S. No. 2,660,062. E. W. Frowe. Iss. 11/24/53. App. 3/17/50. Assign. Robert H. Ray Co.

Gravimeter Apparatus. A vertical acceleration-compensating system for a gravimeter in which motion of the spring-suspended mass controls light to a photocell whose signal is amplified and applied to hydraulic jacks to move the inner instrument case to effect compensation.

MAGNETIC PROSPECTING

U. S. No. 2,659,859. C. A. Heiland. Iss. 11/17/53. App. 4/5/46.

Method of and Apparatus for Aeromagnetic Prospecting. A pendulously-mounted magnetometer having an earth inductor rotating on an axis transverse to the pendulum and whose azimuthal orienta-

* Gulf Oil Corporation, Patent Department.

tion is held in the plane of the magnetic meridian by a servomotor controlled from a flux-gate compass, the measured component of the field being automatically compensated by a pair of current-carrying coils whose current is recorded.

U. S. No. 2,661,455. A. J. Tickner. Iss. 12/1/53. App. 2/13/43.

Flux Measuring System. A flux-valve having two saturable cores in the arms of a transformer-excited bridge circuit and with the output connected to bridge-connected peak rectifiers with the difference between peaks indicated.

U. S. No. 2,663,843. W. E. Wickerham and O. K. Doolen. Iss. 12/22/53. App. 8/3/50. Assign. Gulf Research & Development Co.

Magnetic Gradiometer. A magnetic gradiometer for use with a mobile recording magnetometer comprising a generator mechanically coupled to the magnetometer's nulling-current potentiometer and whose output voltage is proportional to the time rate of change of nulling current from which the space gradient of magnetic intensity is obtained from the known speed of magnetometer traverse.

RADIOACTIVITY PROSPECTING

U. S. No. 2,656,470. G. Herzog. Iss. 10/20/53. App. 3/9/48, 3/19/51 and 8/7/51. Assign. The Texas Co.

Prospecting. A method of airborne radioactivity prospecting in which gamma rays are detected with a bundle of pulse-type detectors whose combined output is integrated with time.

U. S. No. 2,656,471. G. Herzog. Iss. 10/20/53. App. 3/19/51. Assgn. The Texas Co.

Prospecting. An airborne radioactivity-prospecting method in which gamma rays are detected with a pulse-type detector and the background is measured with a G-M counter having an efficiency of less than one-half percent.

SEISMIC PROSPECTING

U. S. No. 2,654,874. F. Press. Iss. 10/6/53. App. 6/14/51. Assign. Socony-Vacuum Oil Co., Inc.

Seismic Exploration System. A seismic recording system in which the airborne wave at each geophone station is picked up by a microphone whose output is mixed with the geophone signal to cancel the effect of ground roll.

U. S. No. 2,656,003. T. C. Poulter. Iss. 10/20/53. App. 2/27/48. Assign. Institute of Inventive Research.

High Explosive Disk-Shaped Charge for Seismic Exploration. A system of seismograph shooting in which a grooved disk of explosive is detonated above ground, the wave from the horizontal surface of the disk being attenuated by a protective shield below the disk.

U. S. No. 2,656,422. G. B. Loper. Iss. 10/20/53. App. 10/25/48. Assign. Socony-Vacuum Oil Co., Inc.

Gain Control System for Seismic Amplifiers. An r-c circuit for time-gain control of a seismograph amplifier which has two condensers in series, one of which is discharged through a constant-current load and the other through a fixed resistance.

U. S. No. 2,657,373. R. G. Piety. Iss. 10/27/53. App. 9/6/49. Assign. Phillips Petroleum Co.

Apparatus for Seismic Exploration. A system for eliminating ground roll in seismic recording by mixing with the signal from a vertical seismometer the proper ratio of integrated signal from a rotational seismometer of the same type.

U. S. No. 2,657,374. T. Bardeen. Iss. 10/27/53. App. 11/2/49. Assign. Gulf Research & Development Co.

Suspension System for Seismograph Detectors. A system for suspending the moving element of a seismometer in which a non-linear magnetic astatizing force is applied to a cantilever spring suspension so that an easily adjustable low natural frequency may be attained without loss of ruggedness.

U. S. No. 2,658,578. C. W. Oliphant. Iss. 11/10/53. App. 10/5/48.

Seismic Prospecting. A method of seismic prospecting in which all three components of ground motion at a plurality of receiving points are recorded as separate traces.

U. S. No. 2,658,579. F. Rieber. Iss. 11/10/53. App. 8/17/49. Assign. Geovision, Inc.

Geophysical Display System. A system for analyzing a group of seismograph records having the traces recorded as light tracks by scanning the records with a television pick-up tube and reproducing the traces or combinations of them with time shifts corresponding to weathering and angularity.

U. S. No. 2,659,064. R. G. Piety. Iss. 11/10/53. App. 8/19/49. Assign. Phillips Petroleum Co.

Rotational Seismometer. A variable air-gap condenser type rotational seismometer having an axially-suspended inertia member with radial condenser plates and closely spaced plates mounted on the case.

U. S. No. 2,659,065. R. L. Cordell. Iss. 11/10/53. App. 8/11/50. Assign. Stanolind Oil and Gas Co.

Seismometer. A cylindrically symmetrical seismometer with equal response to transverse motion in any azimuth having a cylindrical magnet structure and a coil suspended on an axial cantilever in an unsymmetrical position due to the action of gravity.

U. S. No. 2,661,464. A. Wolf. Iss. 12/1/53. App. 4/8/49. Assign. Geophysical Research Corp.

Method and Apparatus for Recording Dip of Geological Strata. A seismograph recording system in which a signal proportional to the dip of the reflecting horizon is obtained from modulator circuits in the geophone channels and recorded on the seismogram with the geophone traces.

U. S. No. 2,661,622. J. Severs. Iss. 12/8/53. App. 7/22/47. Assign. Hartford National Bank and Trust Co.

Electric Vibration Pick-Up. A crystal-type vibration pick-up whose crystal is mechanically connected to a moving-coil transducer which may be driven at a standard amplitude by an oscillator to calibrate the crystal.

U. S. No. 2,662,126. R. L. Henson, Iss. 12/8/53. App. 3/23/50. Assign. Sun Oil Co.

Seismographic Amplifier Mixing Circuits. A seismograph mixing system in which each channel has a cathode follower which is coupled to the channel output stage through a resistor and also coupled to the adjacent stage through a mixing resistor.

U. S. No. 2,663,002. L. B. McManis and J. R. Cooper. Iss. 12/15/53. App. 6/20/50. Assign. Stanolind Oil and Gas Co.

Attenuator for Seismic Gain Control. A seismograph avc circuit using biased diodes connected in a bridge circuit with the signal across one diagonal and the rectified control signal across the other diagonal.

WELL LOGGING

U. S. No. 2,654,960. J. C. Hewitt. Iss. 10/13/53. App. 7/7/52.

Well Instrument, Including Pressurized Battery. A well instrument whose battery is enclosed in a sealed compartment with an aqueous liquid which expands with temperature so as to subject the battery to high pressure at high temperature.

U. S. No. 2,655,632. E. V. Murphree. Iss. 10/13/53. App. 5/12/51. Assign. Standard Oil Development Co.

Electrical Resistivity Dip Meter. A three-electrode electrical dip meter having a current electrode which is held stationary in the well and three pairs of potential electrodes which are carried on caliper arms from an associated orientation apparatus which is movable below the current electrode by a winch in the current-electrode carrier.

U. S. No. 2,656,613. R. W. Goble. Iss. 10/27/53. App. 4/7/48. Assign. Eastman Oil Well Survey Co.

Apparatus for Calipering Well Bores. A well-calipering apparatus having arms whose average position is mechanically transmitted to a vacuum-tube strain gauge which varies the pulse frequency of an oscillator whose frequency is recorded at the surface.

U. S. No. 2,658,284. J. J. Arps. Iss. 11/10/53. App. 1/3/49.

Continuous Directional Drilling. A system for observing the deviation of a borehole while drilling by releasing a radioactive material at the bottom of the hole at a rate proportional to the deviation and observing its concentration in the drilling fluid at the surface.

U. S. No. 2,659,011. A. H. Youmans and R. Monaghan. Iss. 11/10/53. App. 5/23/51. Assign. Well Surveys, Inc.

Method and Apparatus for Compensation for the Effects of Temperature and Voltage Fluctuations on Scintillation Counters. A radioactivity logging apparatus having a scintillation counter with photomultiplier tube and in which the effects of temperature and voltage variation are eliminated by having in the instrument a separate counter and tube excited by an independent radioactive source whose effect is subtracted from that of the logging counter.

U. S. No. 2,659,014. S. A. Scherbatskoy. Iss. 11/10/53. App. 7/5/51. Assign. Perforating Guns Atlas Corp.

Radioactivity Well Logging System. A system for simultaneously making a gamma-ray log and a neutron log over a single-conductor cable by using self-balancing follow-up systems which operate on different frequencies to record the signals from the two detectors at the surface.

U. S. No. 2,659,046. J. J. Arps. Iss. 11/10/53. App. 10/19/48.

Geophysical Exploration Using Radioactive Material. A system of logging while drilling by releasing at the bottom of the hole a radioactive tracer at a rate proportional to the parameter being logged and observing at the surface the concentration of the tracer in the drilling fluid.

U. S. No. 2,659,160. G. A. Smith. Iss. 11/17/53. App. 11/14/47. Assign. Sperry-Sun Well Surveying Co.

Well Surveying Instrument. A well-surveying device having a magnetic needle suspended on a transverse axis in a bifurcated longitudinal pivoted shaft so that the needle remains horizontal even for large inclinations of the borehole.

U. S. No. 2,660,800. B. F. Wiley. Iss. 12/1/53. App. 1/4/50. Assign. Phillips Petroleum Co.

Borehole Hydraulic Measuring Apparatus. A caliper logging apparatus in which the inner end of the caliper arms rest against a bellows containing hydraulic fluid which moves a spring-biased piston mechanically linked to a variable resistance.

U. S. No. 2,660,887. F. Frei. Iss. 12/1/53. App. 9/1/50.

Method for Detecting the Source and Analyzing the Flow of Water Intrusions in Oil Wells. A method of identifying whether water entering a well is leakage through a cement seal by adding to each cement seal a different identifiable substance whose presence in leakage water may be detected.

U. S. No. 2,664,542. R. D. Lynn. Iss. 12/29/53. App. 7/24/52. Assign. Standard Oil Development Co.

Magnetic Well Logging Apparatus. A magnetic logging apparatus which measures the vertical gradient of the horizontal magnetic component by rotating on a common vertical shaft two inductor coils connected in parallel opposition and measuring the amplitude of the difference voltage and its phase with respect to the voltage of one of the coils.

MISCELLANEOUS

U. S. No. 2,657,013. E. F. Brady. Iss. 10/27/53. App. 3/12/49. Assign. Eastman Oil Well Survey Co.

Core Orienting Apparatus and Method. A core barrel into which a testing apparatus may be lowered by a wire line and which tests whether the core is integral with the strata, marks the core, and photographically records the azimuthal orientation of the mark and the inclination of the borehole.

U. S. No. 2,659,433. H. M. Brown. Iss. 11/17/53. App. 2/3/50. Assign. Clemson Agricultural College of South Carolina.

Porosity Tester. A porosimeter in which a weighted piston forces fluid through the sample and the descent of the piston is automatically timed.

U. S. No. 2,659,985. R. T. Cloud. Iss. 11/24/53. App. 8/16/47. Assign. North American Geophysical Co.

Method of and Apparatus for Pendulum Compensating. A system for compensating the pendulum of a vehicle-transported elevation-difference meter for acceleration by generating a signal proportional to the acceleration, differentiating this signal, and applying it to the servo-system controlled by the pendulum to neutralize the effect of the acceleration on the servo system.

U. S. No. 2,661,897. G. Herzog and B. D. Lee. Iss. 12/8/53. App. 6/10/49. Assign. The Texas Co.

Electrical Analogue. A potentiometric model in which the effect of infinite extent of the medium is simulated in a finite model by a boundary on which are located a series of electrodes connected to impedances which produce the same current flow at the model boundary as at the corresponding surface in the medium.

U. S. No. 2,661,898. F. W. Bubb. Iss. 12/8/53. App. 1/8/51. Assign. Phillips Petroleum Co.

Pumping System Analogue. An electrical analogue of a well-pumping system having electrical lines to represent the tubing, oil column, and sucker rod string with the charge on condensers representing displacements, inductances representing inertia, voltage representing stresses, and resistances representing friction and viscous drag.

U. S. No. 2,663,088. R. T. Cloud. Iss. 12/22/53. App. 4/3/48. Assign. North American Geophysical Co.

Pendulum and Acceleration Compensation System. A vehicle gradometer having a pendulum which carries an armature in an air gap between two electromagnets which are energized by a current proportional to the time integral of the vehicle acceleration to exert a force on the armature to balance the effect of the acceleration on the pendulum.

SELECTED LIST OF U. S. PATENTS ISSUED DURING THE FOURTH QUARTER OF 1953

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2,654,242	188	2,656,470[a]	308	2,658,391	288
2,654,245	148	2,656,471[a]	308	2,658,398	224
2,654,246	148	2,656,503	228	2,658,451	136
2,654,247	148	2,656,504	232	2,658,578[a]	360
2,654,285	360	2,656,505	520	2,658,579[a]	360
2,654,287	420	2,656,519	4	2,658,681	68
2,654,666	136	2,656,530	316	2,658,725[a]	208, 116, 516
2,654,681	224	2,656,532	316	2,658,726	80
2,654,808	224	2,656,606	444	2,658,762	224
2,654,809	224	2,656,611	200	2,658,763	484
2,654,818	460	2,656,613[a]	44	2,658,950	224
2,654,833	312	2,656,616	520	2,658,951	224
2,654,874[a]	360, 356	2,656,714	228	2,658,952	224
2,654,881	316	2,656,722	288	2,658,953	224
2,654,883	316	2,656,723	288	2,658,956	224
2,654,884	316	2,656,726	16	2,658,993	312
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2,655,034	412	2,657,277	224	2,659,041	16
2,655,037	428	2,657,315	308	2,659,046[a]	208, 304, 516
2,655,041	148	2,657,319	12	2,659,064[a]	376
2,655,043	288	2,657,341	200	2,659,065[a]	376
2,655,046	16	2,657,350	16	2,659,076	316
2,655,426	324	2,657,355	228	2,659,077	316
2,655,427	324	2,657,358	160	2,659,078	316
2,655,561	224	2,657,373[a]	360	2,659,079	316
2,655,562	224	2,657,374[a]	376	2,659,080	316
2,655,631[a]	144	2,657,377	224	2,659,082	316
2,655,632[a]	116	2,657,380[a]	132	2,659,160[a]	520, 216
2,655,633	520	2,657,381	312	2,659,232	428
2,655,648	312	2,657,471	216	2,659,233	428
2,655,649	316	2,657,572	496	2,659,234	460
2,655,650	312	2,657,577	200	2,659,390	288
2,655,993	48	2,657,579	200	2,659,433[a]	88
2,656,003[a]	360, 136	2,657,581[a]	180	2,659,554	16
2,656,100	68	2,657,969	324	2,659,574	448
2,656,101	68	2,658,113	224	2,659,575	448
2,656,102	68	2,658,114	224	2,659,589	4
2,656,419	224	2,658,186	436	2,659,650	324
2,656,420	224	2,658,195	316	2,659,651	324
2,656,422[a]	372	2,658,284[a]	308, 520	2,659,652	324
2,656,444	288	2,658,384	148	2,659,821	236
2,656,458	12, 484	2,658,385	148	2,659,822	236
2,656,468	196	2,658,389	200	2,659,825	308

* A key to the subject classification system will be found in GEOPHYSICS, v. 12, p. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

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2,659,826	308	2,661,466[a]	132, 320	2,662,978	68
2,659,829	484	2,661,467	316	2,662,980	484
2,659,857	228	2,661,622[a]	492	2,662,985	200, 308
2,659,858	228, 140	2,661,623	448	2,662,996	484
2,659,859[a]	232	2,661,624	16	2,663,002[a]	372
2,659,882[a]	132, 320	2,661,626	288	2,663,004[a]	124
2,659,883	316	2,661,714	140, 12	2,663,014	316
2,659,984	16	2,661,754	288	2,663,015	316
2,659,985[a]	444	2,661,897[a]	68	2,663,017	312
2,660,054	140, 12	2,661,898[a]	68	2,663,084	200
2,660,056	16	2,661,899	68	2,663,085	428
2,660,057	148	2,662,120	484, 224	2,663,088[a]	444
2,660,058	200	2,662,126[a]	356	2,663,188	148
2,660,059	200	2,662,184	236	2,663,190	188
2,660,062[a]	180	2,662,185	236	2,663,191	460
2,660,086	420	2,662,188	308	2,663,379	252
2,660,118	136	2,662,207	16	2,663,520	16
2,660,402	80	2,662,208	308	2,663,610	324
2,660,510	160, 324	2,662,213	68	2,663,781	288, 484
2,660,622	224	2,662,301	16	2,663,802	308
2,660,700	12, 68	2,662,393	168	2,663,838	16
2,660,703	320	2,662,394	412	2,663,843[a]	232
2,660,704	140	2,662,395	88	2,664,011	412
2,660,716[a]	388	2,662,404	200	2,664,024	416
2,660,800[a]	44	2,662,408	288	2,664,139	224
2,660,885	496	2,662,409	288	2,664,156	48
2,660,887[a]	508	2,662,411	16, 484	2,664,157	48
2,660,977	16	2,662,474	48	2,664,158	48
2,661,152	68	2,662,539	428	2,664,243	68
2,661,153	68	2,662,689	68	2,664,251	224
2,661,170	16	2,662,704	16	2,664,254	16
2,661,260	324	2,662,705	16	2,664,269	404
2,661,397	224	2,662,706	16	2,664,335	324
2,661,455[a]	232, 216	2,662,738	80	2,664,542[a]	220
2,661,460	288	2,662,803	324	2,664,560	312
2,661,464[a]	360	2,662,956	4		

REVIEWS

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"Symposium on Surface and Subsurface Reconnaissance," *American Society For Testing Materials*, Special Technical Publication No. 122 (1952), 228 pages. $3.00.

Eight of the papers presented before the fifty-fourth meeting of the Society for Testing Materials discussed the application of geophysics to such engineering projects as:

1. Investigation of the foundations for large structures such as buildings, bridges, tunnels, and dams: depth to bedrock; homogeneity of the bedrock; depth to which weathering has progressed in bedrock; and the nature and homogeneity of overburden.
2. Road construction: estimating nature of material in proposed road cuts and location of materials for construction.
3. Investigation of underground water resources.

The eight papers and their authors are:

1. "Earth-Resistivity Tests Applied to Subsurface Reconnaissance Surveys" by R. W. Moore.
2. "Electrical Resistivity Geophysical Method as Applied to Engineering Problems" by H. Leroy Scharon.
3. "Geophysical Measurements of the Depth of Weathered Mantle Rock" by D. Wantland.
4. "The Practical Value of an Earth Resistivity Method in Making Subsurface Explorations" by W. F. Abercrombie.
5. "Application of Seismic Methods to Foundation Exploration" by A. M. Johnson and R. H. Wesley.

6. "Experience with Geophysics in New York State" by P. H. Bird.
7. "Seismology Applied to Shallow Zone Research" by D. Linehan.
8. "Resistivity Reconnaissance" by I. Roman.

These papers are written for the engineer who has had no previous knowledge of geophysics, and therefore the material presented is elementary to the geophysicist. Primarily two geophysical methods, the seismic refraction and the electrical resistivity, are discussed in detail.

The principles of the seismic refraction method, necessary equipment for conducting surveys, detailed discussion of field procedures, and assembly and interpretation of data are presented in a clear, concise manner by Father Linehan. Application of the seismic method to the determination of the weathering depth of igneous rock is given by Wantland, and depth to bedrock below alluvial overburden is presented by Johnson and Wesley. Bird contrasts the application of the resistivity and seismic methods to problems arising in soil mechanics. He concludes that the resistivity method is of little use in determining bed rock depth in New York state while the seismic method is much more reliable. He considers the seismic method to be limited because of: (1) the inability of measuring a low velocity layer below a high velocity layer on the basis of first arrivals alone, (2) the necessity of a layer having a minimum thickness before refractions can be received from it, (3) a decided velocity anisostropy in highly deformed and truncated basement rock, and (4) the inability of elastic waves to pass through thick sections of artificial fill without excessive absorption.

Roman presents the present status of the resistivity method for reconnaissance surveying in a very comprehensive manner and affixes a bibliography of 127 papers. He discusses the theory of the method, then proceeds with instrumentation and detailed descriptions of field procedures. Especially noteworthy are his comments regarding methods of interpretation. He states, "Interpretation is highly personal; no rigid rules can be transmitted from one operator to another. . . . Some methods have theoretical justification in themselves, but the judgment of the operator is important in deciding whether the actual geological conditions may be idealized to utilize the theoretical analysis. Other methods are purely empirical and their application rests upon the experience, reliability, and skill of the operator. Still other methods are largely qualitative and accordingly are likely to be based on intuition or vague judgments. Each method of interpretation must be considered pragmatically, and the conclusions must always be considered as predictions, with a greater or lesser degree of probability that they represent actual geology. . . . There are as many methods of interpretation as there are investigators and some investigators vary their methods to fit the problem."

Scharon makes a similar statement. "The local conditions departed so greatly from those assumed in the theoretical computations that the theoretical method proved of little or no value. Empirical methods, on the other hand, proved quite successful."

The important question confronting the reader is whether the method should be used at all if the geological conditions do not satisfy the basic assumptions necessary for successful application of the method. One cannot form confidence in a method of interpretation that has no theoretical justification. One becomes more resolute in this belief as he studies the typical surveys, presented in these papers, in which the empirical interpretation has been employed.

PAUL C. WUENSCHEL

The Proceedings of the Geophysical Society of Tulsa, Vol. I, 109 pp., 1953.

This Volume I of these "Proceedings" is a memorial volume to Joseph A. Sharpe. It contains material on the Geophysical Society of Tulsa including a brief history, its constitution and by-laws, its officers and charter members, a list of current members, a brief memorial to Dr. Sharpe, abstracts of papers and lectures given before the Society, and a series of technical papers.

The five technical papers, an aggregate of 39 pages, are all on the magnetic susceptibility of rocks and include many data on the results of measurements of susceptibilities and densities of samples and cores from widely distributed areas.

A posthumous paper by Dr. Sharpe on "The Magnetic Susceptibility of Rocks, Its Determina-

tion and Usefulness" includes a 19-page table of susceptibility values, mostly of igneous rocks from surface and well samples from widely different areas including Alaska, Canada, 15 different States, and Cuba.

"Magnetic Susceptibility Measurements on Llano Uplift Rocks," by Virgil E. Barnes lists susceptibility values for a large number of samples from the Central Mineral Region in the form of averages and ranges of values for groups of samples from the same location. For a few of the samples chemical analyses are available from which normative magnetite was computed and curves are given for the relation of susceptibility to magnetite content.

"Magnetic Susceptibility Measurements on Well Cores For Pre-Simpson Paleozoic Rocks," by Virgil E. Barnes, contains individual values from measurements of cores from the Ellenburger in two wells. These include measurements on dolomites over the interval from 14,981 ft to 16,341 ft from a deep Phillips well in Val Verde County and the dolomite and limestone from 7,416 ft to 8,000 ft in a Humble well in Crockett County.

"Magnetic Susceptibility Measurements in West Texas and Southeast New Mexico," by Peter T. Flawn includes individual measurements on basement cores and cuttings (mostly cores) from 96 wells.

"Bibliography of Papers Having Experimental Data on Magnetic Susceptibility," by Harold M. Mooney contains 51 entries. The papers are mostly in English, but with some German and Russian titles.

The Editor of the volume is Robert J. Watson and copies of the "Proceedings" can be obtained from him at the Carter Oil Company, P.O. Box 801, Tulsa, Oklahoma.

L. L. NETTLETON
Gravity Meter Exploration Company
Houston, Texas

Deep-Sea Research, Volume 1—Number 1, Pergamon Press, London, October 1953, 64 pages.

This is the most recent periodical to appear in the literature dealing with one of several diversified phases of the broad subjects of marine geophysics and geology. Its primary objective is the rapid dissemination of information obtained by deep sea expeditions. Using as a criterion the geographic distribution of the 18 members of the editorial advisory board, as well as the three editors and eight authors, this new periodical may be described as international in its scope and representation. In this first issue, the subject matter of the papers is selected from a wide range of oceanographic sciences, including submarine topography features occuring at great depths, contributions of microorganisms to the diagenetic processes occurring in deep sea sediments, and attempts to correlate the results of a transatlantic magnetic survey with topography. In addition, a summary of the results of the Swedish deep sea expedition of 1947–1948 is presented in which emphasis is given to the various types of information obtained during this survey. This expedition is but one of many conducted during the last decade, necessitating the appearance of just such a periodical as *Deep Sea Research*. This publication can serve as a medium for a more efficient, rapid, and unified means of making available to the scientific world, as soon as possible, the published results of these expeditions. It is hoped that successive issues will contain more papers per issue in order to achieve more effectively these worthwhile objectives.

The article in this issue that may be of particular interest to prospecting geophysicists is by B. C. Heezen et al., entitled "Trans-atlantic profile of total magnetic intensity and topography." It contains a brief description accompanied by some excellent maps and cross sections from which the magnetic data and submarine topography between Dakar and Barbados can be studied in some detail with comparative ease. The information on the variation in the total intensity of the earth's magnetic field in this area was obtained by towing a modified AN/ASQ 3A airborne magnetometer from the *Atlantis*. In studying these profiles it should be kept in mind that the results are comparable to those that might be obtained by a conventional airborne magnetic survey over land topography at

flight elevations varying between a few hundred feet to as much as 15,000 feet. This situation is probably one of the major factors responsible for the lack of correlation between the magnetic profile and the submarine topography occurring in a number of instances, particularly in the deep ocean basins, and even in large portions of the mid-Atlantic ridge.

RICHARD A. GEYER

"Model Seismology," T. D. Northwood and D. V. Anderson, *Bull. Seis. Soc. Amer.*, Vol. 43, no. 3, July 1953.

This is a report on some interesting experiments wherein the propagation of pulses in simple geometric situations is studied in the laboratory. Piezoelectric transducers are used to emit and receive pulses which are displayed as "seismograms" on a cathode ray tube. The present paper deals with two particular problems.

The first is the "Lamb" problem dealing with propagation of tremors over the surface of a solid half space. The results obtained are in qualitative agreement with the theory of Lamb but are much more oscillatory in character. This is attributed to inhomogeneity in the concrete used as a model material. This problem is reported in most seismic model work done to date. It is difficult, even in the laboratory, to achieve the homogeneous isotropic elastic medium usually considered by the theory.

The second problem is the change of shape of pulses upon reflection via maximum or minimum time paths. This is done experimentally, using a hemispherical reflector in water. A source and receiver are placed side by side on the axis of the hemisphere, and the change in shape of the reflected pulse is noted as the distance from the reflector is varied. The authors find that, when the reflection time is a minimum (distance less than the radius of the hemisphere), the pulse develops a tail. When the reflection time is a maximum, the pulse develops a precursor. These results are in agreement with a mathematical development given in another paper.[1]

Although the goal of those working with seismic models is to attack problems too difficult for theoretical treatment, this report and most other reports to date deal with phenomena which have been predicted, or at least suspected, from theoretical investigations. The fact that models are capable of duplicating these results gives us confidence in the method, and it is hoped that it will soon be possible to attack some of the more difficult problems.

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"Statistical Study of Waves from Blasts Recorded in the United States," by E. H. Vestine and S. E. Forbush. *Journal of Geophysical Research*, Vol. 58, No. 3, p. 381–400, Sept. 1953.

The authors have treated seismic records by prediction methods quite similar to those of Wadsworth, Robinson, Bryan, and Hurley (GEOPHYSICS, v. 18, July, 1953). The records discussed in the paper were taken at ranges generally greater than 100 km and were examined for evidence of a reflection from the Mohorovičić discontinuity. The residuals, i.e. the differences between the predicted and actual traces, were also examined for signs of this reflection. Due to the high noise level, it was not possible to identify any such event definitely. However, the finite sum autocorrelation function $\Sigma_{n=0}^{N} f(t_n) f(t_n - \tau) / \Sigma_{n=0}^{N} f^2(t_n)$, for fixed τ, when considered as a function of n, exhibited a change in level in the neighborhood of the time of the suspected "Moho" reflection. The authors conjecture that various physical phases of a record might be identified by changes in the stationary level of the autocorrelation function. This is equivalent to the notion that the various phases of a record are distinguishable on the basis of their power spectra. A statistical analysis of the residuals was made in order to check randomness, and it was demonstrated that a large part of the autocorrelated signal was

[1] D. V. Anderson, T. D. Northwood and C. Barnes, "Reflection of a Pulse by a Spherical Surface," *Jour. Acoust. Soc. Am.* v. 24, pp. 271–383, May 1952.

indeed removed by the prediction technique. Whether or not this means that a large part of the useful information was also removed remains an open question.

EUGENE USDIN
Southwestern Computing Service
Tulsa, Oklahoma

"Note on Analytic Tests for Distinguishing Types of Seismic Waves," by E. H. Vestine, *Journal of Geophysical Research*, Vol. 58, No. 3, p. 401–404, Sept. 1953.

From the vanishing of stress at the free surface, and the condition that particle displacement should decrease with depth, the author attempts to formulate a necessary condition for the existence of surface waves. That this condition is not necessary is shown by the example of Rayleigh waves cited by the author. For Rayleigh waves on a semi-infinite elastic solid, the amplitude of vertical particle motion increases with depth up to a certain maximum before decreasing to zero as depth becomes infinite. The condition that for surface waves, amplitude must decrease with depth, holds only asymptotically and not necessarily in the neighborhood of the free surface. Consequently it is not be be expected that the combination of the free surface boundary condition and a condition that amplitude decrease with depth should yield a criterion for distinguishing various types of seismic waves.

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"Note on Publication Costs," by Merle A. Tuve, *Journal of Geophysical Research*, Vol. 58, no. 3, p. 428–429, September, 1953.

This note by the Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, who is also Editor of the *Journal of Geophysical Research*, discusses the two difficult problems which face scientific publications today. One of the problems is financial. This is easily understandable and I shall say no more about it.

However, the discussion of the other problem is so well stated and the suggested remedy is so original that I quote in full:

"The first and most important [problem] is the fact that the flood of publication is overwhelmingly out of proportion to the capacity of an individual mind for receiving information. Every specialized research area has its adjacent fields and its parent sciences, as well as its own principal journals. At our Department, we subscribe to and preserve 126 magazines, plus 56 additional journals which are kept for some years on a more expendable basis. No staff member can begin even to scan this flood of information during each month. Surprisingly, our observation is that the principal mechanism for information about important new researches is still by person to person contact, through visitors and meetings, and it is still an effective mechanism. The future of scientific publication clearly involves something more basic than the simple resolution by government subsidy of financial problems connected with publication. In every special subject, there are only a few places on the face of the earth which are currently centers of research activity and specialized knowledge. Contact with and between these centers in some way may prove the future bases for intelligent scientific publication and the archives problem, replacing the traditional system of broadcasting to every subscriber detailed basic reports on each research problem in all fields of a broad subject."

THOMAS A. ELKINS

Die Ionosphaere, by Karl Rawer, P. Noordhoff N. V., Groningen, Holland, 1953, 182 pages.

Judging from the title alone, it might be suspected that the contents of this book would not have any particular appeal to prospecting geophysicists. However, the subtitle "Its Significance to Geo-

physics and Radio Communications," gives the first indication that some of the material presented has direct application to the solution of certain problems present in routine geophysical prospecting, including communications, position location and even sources of "noise" in certain types of electrical as well as magnetic prospecting methods. The author has done an excellent job in striking a usefui balance between the theoretical background material necessary to a successful understanding of the phenomena described, and the actual application of this information. He has summarized the available information on these subjects without losing any pertinent details. The thoroughness with which he has covered the subject is evidenced by the very complete bibliography of 143 references appearing in an extremely diversified group of periodicals and books.

Although emphasis in the five chapters is placed on the pure aspects of the study of the ionosphere, Chapters 4 and 5 contain information on both periodic and aperiodic variations in electrical and magnetic properties of the ionosphere. This is most helpful in understanding some of the causes of anamolous propagation of various types of electromagnetic waves used by prospecting geophysicists for both communication and position locating, as well as certain prospecting methods. One such subchapter dealing with methods for calculating field strength and another describing criteria for determining the lower boundaries of useful frequencies are worth considerable study. The variation of electromagnetic wave propagation characteristics with time, geographic location, and elevation above the surface of the earth are all discussed in some detail for several of the principal wave bands now in common use.

RICHARD A. GEYER

"Anhydrite-Gypsum Equilibrium Relations," by Gordon J. F. MacDonald, *American Journal of Science*, Vol. 251, (December, 1953), p. 884–898.

This paper may be of interest to those geophysicists who are working in areas of salt dome caprock or of evaporite deposits and are interested in the geochemistry of the formation of those deposits. The paper considers the thermodynamic relations controlling the equilibrium of anhydrite and gypsum in solution. Thermodynamic calculations are based on the liquid phase being under the pressure of a fluid column whereas the solid phase is under the pressure of the weight of overlying rocks and therefore is about 2.4 times as great. These pressure relations together with a consideration of the earth's temperature gradient and salt concentrations in the liquid lead to a calculation that at depths from 1,300 to 1,800 feet (depending on the amount of dissolved solids) gypsum would not be in equilibrium with pore space water and that anhydrite rather than gypsum should exist below this depth. This calculation is roughly confirmed by observation that in most salt dome caprock gypsum is not found at depths greater than around 1,200 to 2,000 ft. The paper also considers the sequence of anhydrite, gypsum, salt and carbonate rocks in bedded evaporites and attempts to determine the temperature of the environment of deposition. These calculations indicate that for certain observed sequences the temperature would have to be lower than 7°C.

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"The Relationship Between Microseism Period and Storm Position," William L. Donn, *Science*, Vol. 119, No. 3080, January 8, 1954, p. 55–57.

"A Study and Evaluation of the Tripartite Seismic Method of Locating Hurricanes," William L. Donn and Maurice Black, *Bull. Seis. Soc. Am.*, Vol. 43, No. 4, Oct. 1953, p. 311–330.

Microseisms seriously affect the gravity and seismic operations of geophysical exploration. Moreover, storms at sea, which are considered to originate microseisms, are a constant threat to offshore drilling as well as exploration. The two papers by Donn and his co-author present information on the origin of microseisms and on the problem of using microseisms to locate storms.

The first paper attempts to establish a relationship between microseismic period and storm location by the study of data accumulated over a period of several years. The effects of 16 hurricanes on 15 seismic stations were analyzed. The hurricanes traveled over the Gulf of Mexico, the Caribbean Sea, and the western North Atlantic Ocean. There appears to be an obvious correlation between period and water-, or water-and-sediment-, depth under the storm. The average periods range from a short period of 2.3 sec in the Gulf of Mexico to 5.9 sec in the deep southeast of Bermuda. The data indicate that the period-depth relationship can not be definitive enough to compete with other tracking techniques. However, the data give important evidence for the storm-generation of microseisms.

The second paper evaluates the effort by the U. S. Navy to track hurricanes in 1950 by triangulating from a system of three seismic recorders. The original effort was discouraging because the error between the computed and actual storm positions was greater than the theoretical error. This discrepancy is attributed by Donn and Black to "instrumentation and procedure, lack of wave coherence of the three elements . . . , and refraction or multiple wave parts." Improvements are suggested but it is concluded that the "operational value of tripartite stations in tracking storms is small" and that attention be confined to investigation of "the origin and propagation of microseisms before further operational application is attempted."

NELSON C. STEENLAND

"On Geophysical Effects of Freezing," E. J. Workman, *Science*, Vol. 119, No. 3080, Jan. 8, 1954, p. 73.

The article discusses chemical and electrochemical effects resulting from the formation of ice from solutions containing ionic compounds. The phenomena may be of interest to those engaged in mineral prospecting. The author mentions, for example, that electrolytic deposition of copper from such solutions "may be responsible for some native copper occurrences."

The article recognizes that the data under discussion result from controlled laboratory experiments. Yet it considers that the basic electrical behavior has been established in the growing of ice from sea water and that the phenomena are significant in the separation of solutes from terrestrial water.

NELSON C. STEENLAND

Outlines of Structural Geology, 3rd Ed., E. Sherborn Hills, John Wiley & Sons, Inc., New York, 1953, 182 pages. $3.00.

The publication of the Third Edition of "Outlines . . ." is a good occasion for calling attention to the geophysical profession of this small volume which is probably relatively unknown. The First Edition appeared in 1940.

The book is probably more suitable for the extra curricular reading of a geophysicist than others of its type. Its material goes far toward establishing a bridge between the earth's deformational forces and the resulting geologic structures. The content is, therefore, appealing to the physicist. The structure-force relationship is not demonstrated with the rigor of mathematics; by far and large it could not be. The demonstration is effected by numerous, detailed discussions, photographs, and sketches of large scale (mountains), local (isolated folds and faults), and microscopic (petrofabrics) structures which show the dependency of the structural elements to the forces involved. Some simple principles are developed which can be extremely useful to the structural geologist, of course, but even to the interpreter of seismic, gravity, and magnetic data. At least, that has been the reviewer's experience.

After a chapter on Non-diastrophic Structures (i.e., slumpage), the Mechanical Principles of such deformation are presented. These are then applied in turn to Major Crustal Structures, Folds, Faults, Structures of Igneous Rocks, and Petrofabric Analysis. The entire argument of "Outlines" would undoubtedly be lost to anyone uninitated into elementary structural geology. On the other

hand, the material would be very rewarding to the practicing geophysicist who has dealt with geology long enough to be aware of its caprices or problems.

The Third Edition is not substantially different from the earlier ones. The major revision is the presentation of the modifications to some of the former tenets of geology that research and knowledge since World War II have effected.

A last complimentary word is directed to the conciseness of style and presentation which, however, was not accompanied by poor documentation, for the volume is replete with references to the publications of others and with factual data from the author's own experiences.

NELSON C. STEENLAND

An Introduction to the Theory of Seismology, 2nd Edition, by K. E. Bullen, New York: Cambridge University Press, 1953, 296 pages. $6.50.

When the first edition of Prof. Bullen's book made its appearance in 1947, it was enthusiastically received by seismologists everywhere as a first-rate intermediate-level text on the principles and, to a more limited extent, the practice of earthquake seismology. The principal weakness of that edition was its almost complete omission of bibliographic references, an omission which the author justified at the time on the rather questionable basis that the book was only intended as an introduction to the subject.

The second edition remedies this deficiency quite adequately by inclusion of a 20-page bibliography on earthquake seismology, with references as recent as 1953. A close comparison with the first edition indicates that few other revisions were made. Even the new references are not keyed to the text, except in one footnote.

Such additions as were introduced are generally confined to occasional sentences added at the ends of pre-existing sections. The original one-page section on seismic prospecting has a new paragraph on the Heligoland explosion records of 1947, although the connection is not entirely obvious to the reviewer. The concluding section, "Atomic Bombs and Seismology," has six new lines at the end. A few new lines are added on "Microseisms."

For those not owning the first edition, the second edition is recommended on the basis that it contains all the valuable features of the first edition plus a bibliography. Those who do own the first edition will have to decide whether the bibliography is worth the cost of the new edition since they will find very little else in it that they do not already have.

MILTON B. DOBRIN

PUBLICATIONS RECEIVED

American Journal of Science, v. 251, nos. 11 & 12 (Nov. & Dec., 1953); v. 252, no. 1 (Jan., 1954)
Annales de Geophysique, v. 9, no. 4 (Oct. & Dec., 1953)
Beihefte zum Geologischen Jahrbuch, v. 6 (Oct., 1952), v. 7 (Dec., 1952), v. 8 (Aug., 1953), and v. 9 (Aug., 1953)
Bulletin of the Earthquake Research Institute (Tokyo), v. 31, pt. 3 (Sept., 1953) and supplementary v. 4, pt. 1 (Aug., 1953)
Bulletin of the Seismological Society of America, v. 43, no. 4 (Oct., 1953)
Economic Geology, v. 48, nos. 7 & 8 (Nov. & Dec., 1953)
Erdol and Köhle, v. 6, nos. 10, 11 & 12 (Oct., Nov. & Dec., 1953)
Geologisches Jahrbuch, no. 67 (1953)
Geophysical Notes (Tokyo), v. 6, no. 1 (Feb. 4, 1953)
Precambrian, v. 27, no. 1 (Jan., 1954)
Proceedings of the Geophysical Society of Tulsa, v. 1 (1953)
Quarterly Journal of the Geological Society of London, v. 109, pts. 1 & 2 (1953)
Report of the Kakioka Magnetic Observatory, no. 17 (1953)
Science, v. 118, nos. 3071–3078 (weekly November 6 through December 25, 1953) and v. 119, nos. 3079–3083 (weekly January 5 through February 1, 1954)
Science Reports of the Tohoku University, 5th Series, Geophysics, v. 5, no. 1 (August, 1953)
Scientific Monthly, v. 77, nos. 5 & 6 (Nov. & Dec., 1953)
Tellus, v. 5, no. 3 (Aug. 23, 1953)

SOME VALUES AVAILABLE TO STUDENTS*

L. Y. Faust†

It is my understanding that this meeting is for the purpose of considering the reactivation of your student geophysical society. I would like to relate some of my own experiences with scientific societies in the hope of suggesting certain values for your consideration in determining what type of program is most suitable to your requirements.

As an undergraduate student of physics I had the opportunity of attending my college scientific society. At stated intervals speakers addressed the members on scientific subjects leveled at the common denominator of the student audience. We found these talks both stimulating and valuable. In our senior year, however, our background in physics was above this common denominator. The topics seemed too elementary. Possibly we began to suspect that we knew all the essentials of physics. If so, the denouement was disillusioning.

Later I was one of a group of graduate students at the University of Pennsylvania where new opportunities were available: The Franklin Institute of Philadelphia invited all interested students in the vicinity to its meetings. This was in the period from 1928 to 1930 when the Bohr theory of the atom was in its heyday. Schroedinger's wave theory of the atom had been published just recently. The experiments on the diffraction of the electron by Davisson and Germer of the Bell Telephone laboratories and by Thompson at the University of Glasgow were current news. We were privileged to hear both Germer and Thompson describe their discoveries in talks sponsored by the Franklin Institute.

Many renowned physicists addressed us on various occasions. Weyl of the Bureau of Standards spoke on his determination of the weight of the earth, and Professor Wood of Johns Hopkins University described some experiments on ultrasonic waves. These presentations were on an advanced level, being directed mainly to the Fellows of the Institute. However we found most of the material to be understandable.

Other lectures under Franklin Institute sponsorship were directed primarily to the students. One set of lectures was designed to show students the various professional opportunities for physicists. Hull of General Electric, developer of the thyratron, spoke on "Physics in Industry." Arthur H. Compton spoke to us on opportunities for research in physics as sponsored by a university. In the final meeting Karl T. Compton, then Professor of Experimental Physics at Princeton, spoke to us on the opportunities in teaching physics. In his opening remarks he pointed out that while both industrial and university research were concerned with atomic theory, the problem of the teachers of physics was more general: they were interested in photons, protons, electrons, and morons! Although the talks at Franklin Institute were generally understandable to our group, there was no chance for us to become complacent as to our knowledge of physics.

Certain meetings of the Bartol Foundation were open to us. The director of the Foundation, W. F. G. Swann, frequently lectured on abstract theoretical physics. Our first introduction to such lectures left us aghast. We were lost in a maze of equations. However, discussions with our professors concerning the subject matter and careful attention at succeeding lectures began to pay off. We soon found that a larger and larger part of what was being said was comprehensible. Evidently we were training ourselves to understand scientific papers. One memorable experience was an informal meeting at which Dr. Swann introduced Professor Sommerfeld, who was then on a visit to the United States from Germany. At this meeting Professor Sommerfeld addressed us on modern aspects of atomic

* An address delivered October 8, 1953 to the students in geophysics at the University of Tulsa on the occasion of a meeting of that group to consider the reactivation of their student society.

† Amerada Petroleum Corporation, Tulsa, Okla.

physics, but the presentation rather quickly developed into a conversation between Swann and Sommerfeld in which the audience was forgotten. They dealt in terms far beyond the scope of our group. Despite the fact that we could not follow their discussion, we left this meeting with the feeling that listening to them had been a rare privilege. This was not a simple case of hero worship; we did obtain much of value from this abstruse discussion.

In addition to the lectures sponsored by various foundations, we also attended a bi-weekly colloquium in physics at the University of Pennsylvania. Students spoke on assigned topics or on their own research problems. The presentation was followed by general discussion in which all or most of the students participated. Our professors and some of the research men from Bartol Institute and other institutions were also present and entered into the discussion. In these meetings we had the opportunity to learn scientific exposition. We learned, at least to some degree, to enter freely into the discussion of the papers.

While in many ways the required colloquium was the more practical part of our training, the value of the extracurricular lectures we attended was considerable. They gave direction and meaning to our studies. We discovered the limitations of our knowledge. We saw how the leaders in physics were thinking. We felt that we had grandstand seats at modern physics in the making. We saw the giants of physics in close-up.

I hope that these recollections have served to give you some concept of the value that we place and still place on the rare opportunities that were ours.

The question then arises "How can the students of Tulsa University avail themselves of similar opportunities in geophysics?" In many respects, similar values are now available to you. The distinguished lecturers brought to you under the joint sponsorship of the SEG and the Geophysical Society of Tulsa give you a chance to see and hear some of the eminent men in geophysics. The regular meetings of the local society are extremely worthwhile. Many of the top geophysicists in the industry live in the Tulsa area. They can be seen and heard at these meetings. The discussions following the papers are instructive. The differences of opinion expressed sometimes result in important advances in our knowledge.

The Annual and Regional Meetings of the SEG are valuable. Since most of these are held in other cities, they cannot be classed as opportunities available to all of you. Nevertheless, the most significant papers presented there are published eventually in GEOPHYSICS. This journal has attained a high standard of excellence under the editorships of Mr. Paul Lyons and Dr. Milton Dobrin. GEOPHYSICS is the official magazine of your science. It should be studied. You may find many of the articles difficult to comprehend, but you can always get help from your professors. Incidentally, a good concept of each paper can be obtained by reading the abstract, studying the figures, and reading the descriptions of the figures.

It appears therefore that many of the things which I as a student considered valuable are now available to you. There remains the rather considerable gap which could be filled by your participation in a students' society, preferably associated with SEG. Here papers could be presented by the advanced students and followed by a general discussion. It might be worthwhile to prepare digests of the papers presented before the Geophysical Society of Tulsa, or of the papers appearing in GEOPHYSICS. If these digests were delivered in language understandable by the group as a whole, they would be valuable both to the listeners and to those who prepared them. It should be understood, however, that whether such meetings are quite stimulating or extremely boring depends on yourselves—your efforts and your enthusiasm in carrying out this task. I feel that I speak for most of the geophysicists in this area when I assure you that we will consider it a pleasure and a privilege to aid you in any way that you may desire, whether as counselors, commentators, visitors, or as occasional speakers.

DISCUSSIONS AND COMMUNICATIONS

LETTERS TO THE EDITOR

DELTA-T FORMULA FOR OBTAINING AVERAGE SEISMIC VELOCITY TO A DIPPING REFLECTING BED

October 27, 1953

To the Editor of GEOPHYSICS:

It is common practice in seismic prospecting to employ the reflection time move-out with increasing shot-to-seismometer distance as a basis for computing velocity. This reflection time difference we shall call ΔT.

In obtaining ΔT data for use in computing the average velocity to a reflecting bed, it is frequently inconvenient or impossible to arrange the recording spread along the strike of the bed. In other instances, it may be desirable to determine average velocities from ΔT analysis of a prospect which was shot on a routine basis with little or no appreciation as to the relative angles between the recording set-ups and the structural strikes.

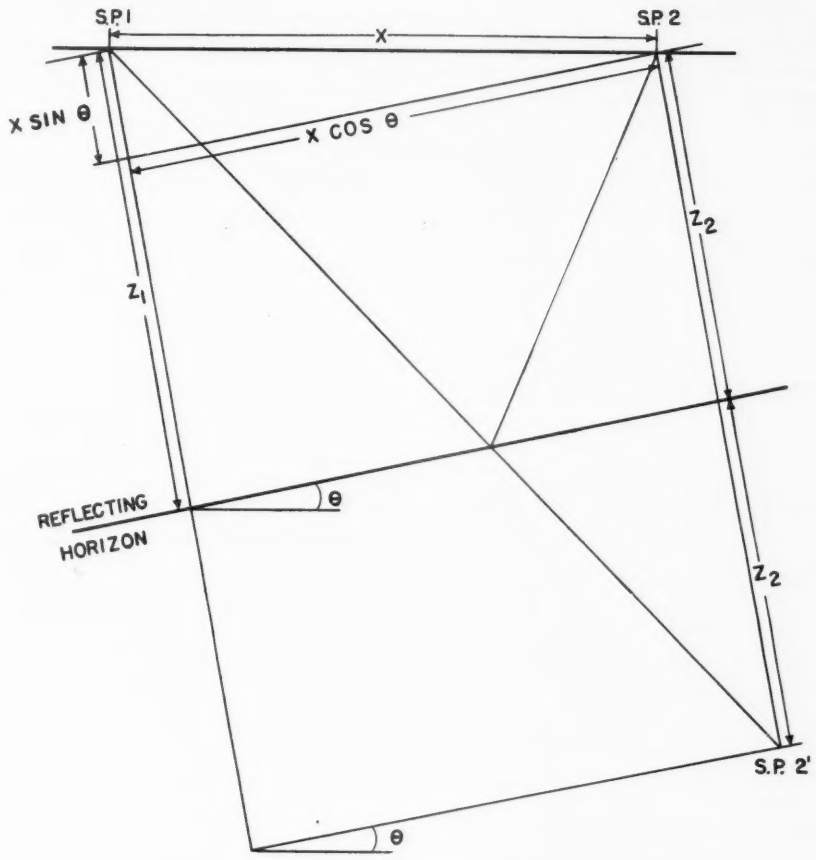

FIG. 1. Geometry of reversed reflection paths for a dipping bed.

Previously published descriptions of velocity computations from seismic reflection data generally ignore dip of the reflector or contain a factor specifically accounting for dip (Green, 1938; Gardner, 1947; Widess, 1952). The following derivation presents a formula for obtaining average velocity independently of the dip of the reflecting bed.

Assumptions:

(1) The reflecting bed is dipping uniformly.
(2) All travel paths are straight lines.
(3) The average velocity to the reflecting bed from two adjacent shotpoints is the same.
(4) Travel times are pulse transit intervals from shot to seismometers.

Figure 1 illustrates the geometry involved. From it we see that
x = Distance between two shotpoints
z_1 = Normal distance to the reflecting horizon from Shotpoint 1
z_2 = Normal distance to the reflecting horizon from Shotpoint 2
θ = The angle formed in the plane of the seismic travel paths between the reflector and a horizontal line.

Let T_1 and T_2 be the two-way normal times to the reflecting bed from Shotpoints 1 and 2. Let T_3 be the reflection time from one shotpoint down to the reflecting bed and up to the other shotpoint. (The above times are considered corrected times such that the time from Shotpoint 1 to a recording position at Shotpoint 2 will equal the time from Shotpoint 2 to a recording position at Shotpoint 1.)

Construct the mirror image of Shotpoint 2 (SP-2′) to the reflecting bed. Drawing a line connecting SP-2′ to SP-1 establishes the position and length of the long trace energy path between Shotpoints 1 and 2.

The following four basic equations are evident from the diagram:

$$z_1 = \tfrac{1}{2}\overline{V}T_1 \tag{1}$$

$$z_2 = \tfrac{1}{2}\overline{V}T_2 \tag{2}$$

$$(\overline{V}T_3)^2 = (z_1 + z_2)^2 + x^2\cos^2\theta \tag{3}$$

and

$$(z_1 - z_2) = x\sin\theta. \tag{4}$$

Squaring equation (4) and converting the $\sin^2\theta$ to $\cos^2\theta$ gives

$$(z_1 - z_2)^2 = x^2\sin^2\theta = x^2 - x^2\cos^2\theta. \tag{5}$$

$$x^2\cos^2\theta = x^2 - (z_1 - z_2)^2. \tag{6}$$

This expression can be substituted for $x^2\cos^2\theta$ in Equation 3 to yield

$$(\overline{V}T_3)^2 = (z_1 + z_2)^2 + x^2 - (z_1 - z_2)^2, \tag{7}$$

which simplifies to

$$(\overline{V}T_3)^2 = 4z_1z_2 + x^2. \tag{8}$$

Substituting equations (1) and (2) into (8) we obtain

$$(\overline{V}T_3)^2 = \overline{V}^2T_1T_2 + x^2, \tag{9}$$

which can be solved for $\overline{V}$. Thus we have

$$\overline{V} = x/\sqrt{T_3^2 - T_1T_2} \tag{10}$$

which is the required formula, containing no expression for dip.

After determining the average velocity from equation (10), the angle θ can be found by computing z_1 and z_2 from equations (1) and (2) and substituting the values obtained into equation (4) to

determine sin θ. This angle θ is equivalent to the apparent dip in the seismometer line as determined by usual straight path computing methods.

It might be mentioned here that the assumptions listed at the beginning are not universally valid. Thus, θ may be a reasonable approximation to actual apparent dip in gently dipping areas whereas path curvature becomes an appreciable factor in areas where dips are moderate to steep. Deviation of field conditions from assumed conditions, of course, also affects the velocity determination. This is, in general, equally true of straight path ΔT velocity formulas previously described in literature.

It is seen that equation (10) is in one sense a more general ΔT formula than that commonly used to determine the average velocity to flat reflecting beds. When T_1 equals T_2, (i.e., when the reflecting bed is flat), equation (10) reduces to

$$\overline{V} = x/\sqrt{T_3^2 - T_1^2}$$

or

$$\overline{V} = x/\sqrt{\Delta T(2T_1 + \Delta T)},$$

which is the usual flat-bed delta-time formula. In another sense, the new formula is more restricted in that it pertains to the particular reversed surface coverage seismometer spread shown in Figure 1.

The author wishes to thank Geophysical Service Inc. for permission to publish this note.

JOHN C. PFLUEGER
Geophysical Service Inc., Dallas, Texas

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THE USE AND ACCURACY OF SECOND DERIVATIVE COEFFICIENTS

December 23, 1953

To the Editor of GEOPHYSICS:

The number of notes and articles recently appearing in GEOPHYSICS on second derivative methods of interpretation of gravity and magnetic data testifies to the growing interest in such methods. However, various criticisms of coefficient sets presented in my article, "The Direct Approach to Magnetic Interpretation and Its Practical Application," in the July 1949 issue of GEOPHYSICS make it worthwhile to present the following observations.

Since my paper was intended to give a presentation of the complete inverse problem of computing distributions of mass or magnetic material from observed gravity or magnetic field data, in which the computation of second or other even derivatives is a comparatively minor part, it was impossible to include a great mass of work on alternative solutions and methods which had been tested during our study of this problem at the Gulf Research Laboratories. To do otherwise would easily have made the paper the size of the annual volume of GEOPHYSICS. Even to cover the material selected required the omission of much detail in proofs and descriptions of methods. Since some criterion of selection was obviously needed, it was decided to present methods which had been tried and found to work better on actual field data than various alternative methods.

It seems to me that this point of practical utility is of decisive importance; however, it has not been adequately considered by many who write on the subject. In our work we have of course found sets of coefficients of all degrees of precision not only for the second derivative but also for continua-

tion and other purposes. Some of these sets are very accurate on theoretical data of infinite precision but are so sensitive as to be of no value for use on field data, which is necessarily of limited precision. As already stated, only those sets of proven value for general use on field data were included in my paper. This does not imply that other sets may not be equally useful or for special problems may not be more desirable. As a matter of fact, it is good practice to select coefficients to fit problems much as a skilled craftsman chooses tools best fitted to perform the work at hand.

At the time the paper was written it was hoped that other papers would follow which would give detailed treatments of points which could only be dealt with superficially in this first paper. Unfortunately limitations of time have so far made this impossible; consequently it is felt that this brief note will be of value.

LEO J. PETERS
Gulf Research and Development Co.
Pittsburgh, Pa.

SECOND DERIVATIVE CALCULATIONS

January 15, 1954

To the Editor of GEOPHYSICS:

Leo J. Peter's and Thomas A. Elkins' remarks in reference to "Computation of the 'Second Derivative' from Gravity Data" by O. Rosenbach (GEOPHYSICS, v. 18, p. 894–912. October 1953) and the author's reply are very interesting but they cannot satisfy the reader. From Figure "A," one of the two methods of calculation looks better; from Figure "B" the other. Dr. Rosenbach, on p. 912, suggests that his critics may not have applied his computation method carefully enough and requests that they make available to him the observed gravity anomalies in the test area of Figure "A." The same possibility might apply to the example in Figure "B" selected by the author. In this case too it would be desirable for the reader to be able to examine the observed gravity anomalies.

It is a pity that the results of computations are generally given by geophysical periodicals in such a form that the reader does not have the slightest possibility of being able to check their correctness. I do not believe that authors should shirk from such a test. The custom seems to have grown of publishing only gravity contours but not the measured gravity anomalies from which the contours have been drawn.

Not only Mr. Rosenbach but other readers (such as the writer of this letter) would be obliged to Messrs. Peters and Elkins if they would publish the observed data for this and other test areas along with their second derivative maps, however calculated. A mere exchange between individual authors as suggested by Mr. Rosenbach is unfortunately of no value to other readers. It would therefore be desirable if in the future the authors of papers could publish the results of their computations in such a way that they could be checked by reference to the original data.

BRUNO F. J. KUNZ
Rohoel-Gewinnungs A. A.
Salzburg, Austria

ON ANOMALOUS PROPAGATION OF RADIO WAVES IN EARTH STRATA

February 26, 1954

To the Editor of GEOPHYSICS:

Reports have been made from time to time on the possibility of radio transmission to great depths in the earth of the order of 1,000 feet or more. (Barrett, 1949 and 1952). From the standpoint of conventional theory this would appear to be a rather unusual situation. For example for a typical rock resistivity of 10^4 ohm-cm and a frequency of 1,600 kc the classical electrical "skin depth" δ is equal to 4 metres or about 13 feet. This corresponds to attenuations of the order of one decibel per foot.

While the signals may well be detected by a buried receiver at depths down to 100 feet or more it is very doubtful if geological features at such depths would appreciably change the character of the

radio wave on the surface. It is most probable that in most of the radio transmission experiments reported, sufficient care has not been taken to insure that the signal may travel along pipes, wires and other buried conductors. The work of Pritchett (1952) is a notable exception; he was able to ascertain without doubt that the electromagnetic energy passed from transmitter to receiver through the rock media. His results are in good agreement with theory. Criticisms of his paper (see the discussion that follows it) are mostly of an irrelevant nature.

It might be argued that the simple theory is based on the behaviour of plane waves which never exist in actuality. It can be shown, however, that for both horizontal or vertical electric and magnetic dipole antennas that the radiation field strength in the ground varies with the depth z according to exp $(-z/\delta)$ to a good approximation. But the most conclusive theoretical argument is to consider propagation over a stratified medium. It is seen from this work that the propagation is determined entirely by the properties of the upper stratum if its thickness exceeds about 3δ. (Wait, 1953 and 1954; Campbell, 1953).

It is not the purpose of this note to disprove propagation of radio waves to great depths under all conditions. In fact there may well be some rather unusual features that would possibly guide the electromagnetic energy with low attenuation. A hypothetical situation would be an extensive horizontal stratum of very poor conductivity which is bounded above and below by highly conducting material. It is quite possible that such a model may explain certain abnormally low attenuations in the direction of the stratum. For example if a vertical electric or horizontal magnetic antenna is placed in such a layer a transverse magnetic wave-guide mode of zero order can be set up. Higher order modes would only be set up if the thickness of the stratum h were greater than one half of the effective wavelength λ_e. The field strength of the zero-order mode varies inversely as the square root of the distance. Additional attenuation takes place due to the loss tangent of the dielectric and due to the finite conductivity of the walls.

Further theoretical work on this subject will be submitted for publication in the future.

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James R. Wait
Radio Physics Lab.
Defence Research Board
Ottawa, Ont.

MEMORIAL

PAUL JAMES CLINE

These lines are written in honor of a very close friend and professional partner of many years.

Paul James Cline died unexpectedly of a very sudden heart attack while at rest in his home in Dallas, Texas, on Saturday afternoon, December 19, 1953. His untimely passing at an early age of 41 years while fully active in his profession, his business, and his other interests was a severe blow to his many friends and associates as well as a great loss to his family. All will miss him immeasurably.

Paul was born April 30, 1912 in Lawrence, Kansas. He obtained his early education in Wichita, Kansas, where he later attended Wichita University, graduating with a B.S. degree in Chemistry. After graduation from the University he entered geophysical work in late 1934 with the Western Geophysical Company as a seismograph observer in western Kansas. In 1935 he joined the National Geophysical Company where he soon became a party chief, then supervisor and partner. In 1944 he, with several close friends, organized the Seismic Engineering Company of Dallas, Texas where for the last nine years he was prominent in management and

field supervision and contributed greatly to his company's success and reputation in the geophysical industry.

Paul Cline's greatest interests were his family, his friends, his professional acquaintances and associates, and in agricultural projects of his own. He was a Reserve Officer in the United States Army, a member of the Society of Exploration Geophysicists, Dallas Geophysical Society, and, since childhood, a member of the Methodist Church.

Paul married Royce Janette Jones in Oklahoma City on June 1, 1946. He was a devoted father and husband and is survived by his widow, a son and daughter, Henry Cline, aged 4 years, and Mary Martha Cline, 3 years, now living at their home in Dallas, and by a sister, two brothers, and his mother, Mrs. W. F. Cline of Wichita, Kansas.

His many friends, acquaintances and particularly those who were fortunate enough to live and work with him will always remember Paul Cline as an extremely conscientious, kind, and generous person whom it was a great pleasure to know.

C. G. McBURNEY

Jan. 10, 1954

MEMORIAL

LOUIS AUGUST SCHOLL

Louis August Scholl, Jr., after a short illness, died in Houston, Texas, September 22, 1953. His passing was entirely unexpected and was a great shock to his many friends and business associates.

Mr. Scholl, the eldest child of Louis August Scholl, Sr. and Mary Ellen Pritchard Scholl, was born December 31, 1887 in Pittsburgh, Pennsylvania, where he spent the early part of his life. His interest in coal mining, one of the principal industries in Pennsylvania, influenced him to study mining engineering and geology, and he graduated from the Carnegie Institute of Technology with the B.S. degree in Mining Engineering in 1910. Following his graduation from Carnegie Tech, he entered the services of the Candor Mines Company at Candor, North Carolina, as a shift boss in their Cyanide Plant. After approximately one year's service with that company, he was employed by the United States Bureau of Mines at the University of Illinois in Urbana, to make mining investigations. The results of some of his work is published in Bulletin 102, Department of the Interior, Bureau of Mines, entitled "The Inflammability of Illinois Coal Dusts."

During 1914, he resigned from the Bureau of Mines for graduate work at the Columbia University School of Mines, where he received the E.M. degree in 1916.

He entered the service of The Texas Company on July 1, 1916, as a geologist for the Producers Oil Company, Tulsa, Oklahoma. This was later changed to The Texas Company, Producing Department, Oklahoma-Kansas Division. He was made Division Geologist of that division on April 1, 1918, and was promoted to Chief Geologist of The Texas Company at Houston, Texas, on September 1, 1920.

From October 20, 1920 until July 28, 1925, he was engaged in the supervision of geological exploration in South America, chiefly in Colombia and Venezuela, but also including work in Ecuador, Peru, Panama, and Trinidad.

Shortly after returning to the States, Mr. Scholl was granted a leave of absence for about one year for graduate work in the University of California. On returning from leave of absence on June 1, 1926, he served as Consulting Geologist in the New York office until May of the following year, carrying out geological investigations in the province of Alberta, Canada, and in the states of Washington and California.

He was transferred to Houston, Texas, on May 1, 1927, as Consulting Geologist and was made Chief of the Geophysical Division of the Producing Department of The Texas Company on November 1, 1929. On September 1, 1945, to more accurately describe his position, his title was changed to Manager-Geophysical Division. After serving as Manager of the Geophysical Division for a period of approximately five years, he was on April 1, 1950 promoted to the staff of the General Manager-Producing Department at Houston, Texas, and made Geophysical Consultant, which position he held until his normal retirement on December 31, 1952 from the services of The Texas Company.

Mr. Scholl was intensely interested in all phases of the petroleum industry, particularly in the exploration work which was his field of endeavor for over 36 years. His enthusiasm for geology and geophysics was always exceptional. This keen interest combined with his broad experience and sense of values brought recognition from his associates in The Texas Company as an outstanding oil finder. His twenty-one years as head of The Texas Company's geophysical group covered a period of great expansion and changing techniques and is a tribute to his professional ability.

He was always sympathetic and encouraging to the young geologists and geophysicists and his searching questions and discussions were very influential in stimulating their thinking. He was rich in experience and unhesitatingly drew from his wide knowledge of oil exploration for the benefit of the younger men in the organization. Such interest extended to many subjects other than oil finding as was apparent by his ability to discuss them most intelligently.

Mr. Scholl was a member of the Second Presbyterian Church, and a member of the American Association of Petroleum Geologists since 1916, a charter member of the Society of Exploration Geophysicists, member of the Houston Geological Society, Houston Section of SEG., American Institute of Mining and

Metallurgical Engineers, Houston Engineers Club, Texas Academy of Science, National Oil Scouts and Landmen's Association, Seismological Society of America, Delta Upsilon Fraternity, Masonic Order, American Museum of Natural History, and American Petroleum Institute.

Louis Scholl was married to Ethel Bevins in Pittsburgh, Pennsylvania, December 28, 1916. He was always a devoted husband and father and, in addition to his widow, is survived by a daughter, Mrs. Norman H. Peden, of Houston, a son, Captain Louis A. Scholl, III, Randolph Field, San Antonio, and four grandchildren.

Mr. Scholl was very fond of both hunting and fishing. He loved to sit in a duck blind in the early morning when the mallards and pintails were decoying, and it was my pleasure to accompany him on some thrilling antelope hunts.

It was indeed a pleasure to work with and under Mr. Scholl's guidance and direction for eighteen years. His sprightly step, twinkling eyes, good humor, and wise counseling will be grievously missed in the years to come.

ROY L. LAY

Houston, Texas
December 28, 1953

MEMORIAL

RAYMOND O. WINGETT

"He has achieved success who has gained the respect of intelligent men; who has filled his niche and left the world better than he found it."

Raymond O. Wingett died of a heart attack on October 21, 1953 at Houston, Texas. The suddenness of his passing came as a shock to his many friends and professional associates.

Ray was born on February 21, 1909, the son of Oscar R. and Julia Cage Wingett. His birthplace was Washington, Pa., known as "Little Washington," which is situated among the wooded hills of Western Pennsylvania about twenty-five miles south of Pittsburgh. It is here that the strong traits of character were formulated which distinguished him in his work as geologist and geophysicist. As a boy in his teens, he enjoyed the competitive sport of basketball, and as a member of his church team, he played a spirited game and was one of the top scorers in the Y.M.C.A. league of his town.

After graduating from Washington High School in June, 1927, he aspired

with firmness of purpose to higher learning. Being long on resolve but short of money, Ray spent a period prior to furthering his education clerking in a drug store and working at the Hazel-Atlas Glass Company. At this time he also served in Company H of the Pennsylvania National Guard. When Ray had accumulated sufficient funds to resume his studies, he entered the University of Pittsburgh in June, 1929. He commuted daily by train between Pittsburgh and his home in Washington. This permitted him only time for travel and study. Despite the trying times of the depression, he managed to continue his schooling by self-support and received a degree in electrical engineering in June, 1933.

Immediately upon graduating Ray found employment in the Geophysical Department of Gulf Research and Development Company at Pittsburgh. After receiving training in seismic interpretation, he was given a field assignment at Houma, Louisiana. From Houma the seismic crew to which he was attached moved to Smith Point and then to Houston, Texas. In March, 1938, while working out of Houston, he met Pearl Sherlock. In October of that year, they were married at Nashville, Tennessee. In April, 1945 Ray resigned his position with Gulf Research and Development Company to work for Heiland Exploration Company, and in July, 1945, he joined the Division Geophysical staff of the Cities Service Oil Company in Houston. In November, 1946 Ray left the Cities Service Company to become Assistant Division Geophysicist for the Union Oil Company of California in Houston. In 1950 he was promoted to Division Geophysicist. Shortly thereafter he suffered a severe heart attack. On recovery from this he was transferred to the Division Geological staff to work on special geological and geophysical problems. In a remarkably short time Ray acquired a sound geological knowledge which, combined with his rich geophysical background, made him an outstanding explorationist.

His untimely passing is a great loss to the science of oil exploration. With the soundness and practicability of his abilities, he contributed much to the oil exploration industry. He was well qualified to investigate intricate geological and geophysical problems and was doggedly persevering in pursuit of their solution. Ray was an associate member of the AAPG and an active member of the SEG.

Ray was a quiet unassuming man without sham or pretence. His principal hobby was reading and studying. This had been supplemented by a newly acquired hobby of fishing and a new home, both of which were a source of great enjoyment and happiness for Ray and his wife, Pearl, in the closing years of his life.

To his friends and associates Ray leaves a rich legacy in the memory of his honesty, sincerity and determination. He was a devoted husband, a warm friend, and a faithful employee.

Surviving him are his wife, his father, a sister, Mrs. June Seibert, and a niece, Pennyrae Seibert.

HOWARD W. GILES
WAYNE Z. BURKHEAD

January 15, 1954

CONTRIBUTORS

WILLIAM B. AGOCS

WILLIAM B. AGOCS has a background of 20 years experience in geophysical exploration, both by ground and aerial methods. From 1937 to 1940 he was geophysicist in charge of refraction and reflection seismic exploration for Gulf Research & Development Co., here and abroad. From 1940 to 1944 he entered the teaching field in Physics and Geophysics at Lehigh University at Bethlehem, Pennsylvania, and was active as a consultant for oil and mining companies. Agocs returned to active oil exploration as Chief Geophysicist for Venezuelan Atlantic Refining Company at Caracas. There he organized its geophysical operations, working with geophysical and geologic data for explorations both on land and under water. In 1946 he resumed teaching at Lehigh, and in 1948 returned to his work for Venezuelan Atlantic for another two years.

From 1950 to 1953, Dr. Agocs was associated with the University of Tulsa as head of the Department of Geophysics. In addition he served as a consultant on airborne magnetometer surveys and ground magnetic studies for mining and oil companies. His work included surveys in Canada, the United States, Venezuela, South Africa, Southwest Africa, Cuba, and Brazil. His earlier work with oil and mining companies included extensive geophysical field surveys and interpretation of vertical magnetometer control, as well as aeromagnetic data, in foreign and domestic areas.

Later in 1953 Dr. Agocs joined the staff of Aero Service Corporation, Philadelphia, as a consultant on airborne magnetometer surveys and other geophysical survey problems.

He is a member of Sigma Xi, the Society of Exploration Geophysicists, American Physical Society, Institute of Radio Engineers, American Geophysical Union, and Asociacion Venezolana de Geologia, Minera y Petroleo.

HAROLD A. BLUM

HAROLD A. BLUM received a B.Ch.E. degree from Rensselaer Polytechnic Institute in 1942, an M.S. degree in Physical Chemistry in 1948, and the Ph.D. degree in Chemical Engineering in 1950, both from Northwestern University.

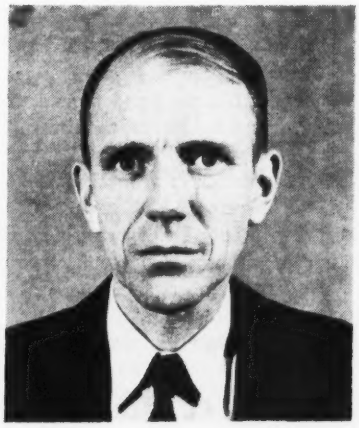
He served as Engineer for the Philadelphia Signal Corps Procurement District from 1942 to 1943, and in the Army Signal Corps from 1943 to 1946. In 1947 he was a teaching assistant in the Chemistry Department of Northwestern University, and from 1948 to 1949 was a research assistant in the Chemical Engineering Department. In 1949 he joined The Atlantic Refining Company, Dallas, Texas, as Senior Physicist in crude oil production research, and he has served as a graduate lecturer at Southern Methodist University since 1951.

Dr. Blum is a member of the American Institute of Chemical Engineers, Dallas Chemical Engineers Club, American Chemical Society, and American Institute of Mining and Metallurgical Engineers.

GUY O. BUCKNER

GUY O. BUCKNER, JR., attended the University of Texas for two years, then as a night school student he received a B.S. in Physics in 1948 and a M.S. degree in Physics at the University of Houston in 1953. During the years 1941–1943 he worked on seismic crews for Rogers-Ray Company, Independent Exploration Company, and Magnolia Petroleum Company. In 1943 he joined The Texas Company Geophysical Laboratory as a draftsman, later becoming an engineer. In 1948 he joined Halliburton Oil Well Cementing Company as an engineer in the Electrical Well Services Laboratory in Houston, the position he now holds.

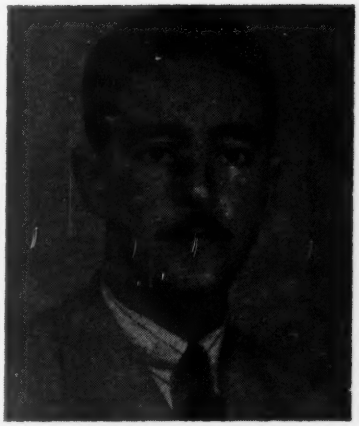
JULIAN F. EVANS received a B.A. degree in 1926 and M.S. degree in 1932 from the University of Oklahoma. He worked on field seismograph crews for several years, after which he returned to school, receiving a Ph.D. degree in physics from Rice Institute in 1939. He taught Physics for one year at Texas Christian University. In 1941 he became a Research Engineer in the Exploration Research Division of the Stanolind Oil and Gas Company laboratories at Tulsa. At the present time he holds a position of Research Associate with that organization. He is a member of the Society of Exploration Geophysicists and the Geophysical Society of Tulsa.



JULIAN F. EVANS

CHARLES F. HADLEY

CHARLES F. HADLEY received his B.S. in 1937 and his M.S. in Electrical Engineering in 1938 from the California Institute of Technology. Upon graduation he was employed by Magnolia Petroleum Company in Dallas, Texas. In 1944 he received a Ph.D. degree in Electrical Engineering from Stanford University. Upon graduation he joined the staff of Radio Research Laboratory at Harvard University where he was engaged in development of microwave measuring instruments used in the radar countermeasure equipment. In 1946 he joined the staff of the Exploration Division of the Research Department of Stanolind Oil and Gas Company in Tulsa. He is now a Senior Research Engineer. He is a member of the Society of Exploration Geophysicists and a Senior Member of the Institute of Radio Engineers.



LINDONOR MOTA

LINDONOR MOTA was graduated as Mining and Civil Engineer in 1945 from the Escola Nacional de Minas e Metalurgia da Universidade do Brasil, Ouro Preto, Minas Gerais, Brasil. Upon graduation he entered the Conselho Nacional de Petróleo, Brasil, as "Engenheiro Especializado" for geological and geophysical work. At present he is Chief of the Office of Administration for the Conselho Nacional do Petróleo in Natal, Rio Grande do Norte, Brasil.

Mr. Mota is a member of American Geophysical Union, Society of Exploration Geophysicists, Sociedade Brasileira de Geologia, and Clube de Engenharia (Brasil).

JACK OLIVER

JACK OLIVER received a B.A. degree from Columbia College in 1947, an A.M. degree in Physics in 1950 and a Ph.D. degree in Geophysics in 1953 from Columbia University.

Since 1947 he has been associated with the geophysics group at the Lamont Geological Observatory working on projects in earthquake seismology, land and shallow water seismic refraction, sound transmission in the atmosphere and in ice, and currently, model seismology. In 1951 he worked for the Air Force Cambridge Research Laboratories conducting seismic and other geophysical studies on the Arctic ice pack north of Alaska. At present he is a Research Associate at the Lamont Geological Observatory.

Dr. Oliver is a member of the Society of Exploration Geophysicists, American Geophysical Union, Seismological Society of America, American Physical Society, and Sigma Xi.

DANIEL SILVERMAN

DANIEL SILVERMAN received the degree of B.S. in Electrical Engineering from the University of California in 1927, the M.S. degree in 1929 and the Sc.D. degree in 1930, both from MIT.

From 1930 to 1934 Dr. Silverman was engaged in research on gaseous-conduction devices for Westinghouse. From 1934 to 1936 he worked for the Arma Engineering Company. The next year was spent at the University of California as Instructor and Assistant Professor of Mechanical Engineering. In 1937 he accepted a position as Research Engineer with the Stanolind Oil and Gas Company. His present position is Exploration Research Director.

Dr. Silverman is a member of Tau Beta Pi, Phi Beta Kappa, and Sigma Xi fraternities, a Fellow of the Institute of Radio Engineers, and a member of the American Physical Society, the Acoustical Society of America, the American Institute of Mining and Metallurgical Engineers, the Society of Exploration Geophysicists, the Seismological Society of America, and The American Association of Petroleum Geologists.

STEPHEN M. SIMPSON, JR.

STEPHEN M. SIMPSON, JR., received a B.S. degree in Physics in 1950 at Yale University and a Ph.D. in Geophysics in 1953 from the Massachusetts Institute of Technology. During 1952 and 1953 he worked with the Geophysical Analysis Group at MIT as a Research Assistant, largely concerned with using digital computers to instrument statistical methods of seismic prospecting. In 1953 he was appointed Instructor of Geophysics at MIT.

Dr. Simpson is a member of Phi Beta Kappa and Sigma Xi.

HAROLD D. SMITH received a B.S. degree in Physics from the Agricultural and Mechanical College of Texas in 1950, and a M.S. degree in Physics from Northwestern University in 1951. Since 1951 he has been in the Research and Development Department of The Atlantic Refining Company, Dallas, Texas.

Mr. Smith is a member of the Society of Exploration Geophysicists, American Institute of Mining and Metallurgical Engineers, and American Physical Society.

HAROLD D. SMITH

JAMES R. WAIT

JAMES R. WAIT attended McGill University for a brief period before enlisting in the Canadian Army in 1942. By the end of the war he was a foreman in a radar R.C.E.M.E. workshop at Kingston, Ontario. He received the B.A.Sc. and M.A.Sc. degrees in Engineering Physics from the University of Toronto in 1948 and 1949, respectively. At this time he was employed as a junior research engineer at the Hydro Electric Power Commission of Ontario. Returning for further graduate work to the University of Toronto, he obtained a Ph.D. degree in Electromagnetic Theory in 1951.

From 1949 to 1952 Dr. Wait was associated with Newmont Exploration Limited, of Jerome, Arizona. At present, he is with the Defence Research Telecommunications Establishment in Ottawa, where he is mainly concerned with theoretical problems in radiation.

For a biography of JOSEPH D. EISLER, see GEOPHYSICS, v. 16, p. 539.

ABSTRACTS OF PAPERS GIVEN AT TECHNICAL CONFERENCE OF U.C.L.A. INSTITUTE OF GEOPHYSICS

NOVEMBER 4–5, 1953

Program of Experimental Rock Deformation

JOHN W. HANDIN, Shell Development Company, Houston, Texas

The objective of this program is the attainment in the laboratory of fundamental knowledge of the inelastic behavior of rocks at the high pressures and temperatures encountered deep in the earth's crust. The experimental data obtained may be of application in at least three important fields of petroleum exploration and production research: structural geology, deep drilling procedures and reservoir mechanics.

Apparatus has been constructed to simulate the natural environmental factors of pressure, temperature, time, simple states of stress, and hydrothermal solutions. Since very little is now known about the inelastic properties of crustal materials, and since only two or three other laboratories in the world are engaged in studies of the problem, the amount of work to be accomplished is nearly limitless. Therefore our current and planned investigations are selected with the hope that results will be helpful in the solution of problems of importance to the oil industry, as well as to the science of geology. To this end we have designed equipment for: 1) short-time triaxial testing to 10,000 atm. and 400°C., 2) compressibility measurements and determination of porosity changes under pressure to 3,000 atm., 3) creep testing at constant load or constant strain rate at confining pressure to 3,000 atm., temperature to 400°C., time to 1,000 hours, 4) studying low grade dynamothermal metamorphism with provision for combined axial and torsional loading, circulating hydrothermal solutions, confining pressure to 3,000 atm., temperature at 400°C., and time to several hours.

We have obtained some data on the strength and ductility of rock salt, and are now studying the flow and fracture of dolomite and the compressibility of sands. We plan to begin work on sandstone cementation and the clay-to-shale-to-slate transformation. Closely allied with the experimental program are the theoretical study of the flow and fracture of solids and the investigation of microscopic and submicroscopic deformation mechanisms. We hope that an integration of the three related approaches to the problem of rock deformation will permit us to apply our results in deciphering earth structures and predicting the mechanical properties of deeply buried rocks.

The Influence of Pressure on the Deposition of Ores

GEORGE C. KENNEDY, Institute of Geophysics, U.C.L.A.

It is apparent that an ore-depositing solution, traveling from its magmatic source to the surface of the earth, undergoes sharp pressure changes as well as temperature changes. Most theorists have considered temperature decrease, with subordinate chemical reaction between solution and wall rock, as the major causes of deposition of ores. The role of pressure change has been neglected.

If we consider an isothermal case, solubility of an ore mineral in a hydrothermal solution is proportional to the chemical potential of the solution, which is, in turn, proportional to the specific volume of the solution. Pressure changes greatly affect the volume of a gas of low density but affect the volume of a high density gas or liquid but little. We may thus set up four possible cases.

1) The hydrothermal fluid is a liquid throughout its entire path. In this case pressure changes can play but an insignificant role, as the compressibility of a liquid is slight and relatively small volume changes take place on release of pressure. Such would be the case if the hydrothermal solution were a solution saturated with alkali halides, for example.
2) The hydrothermal solution is a near ideal gas. In this case deposition should be proportional to the drop in pressure of the solution as it travels upward.
3) The hydrothermal solution is a non-ideal gas. In this case little deposition due to pressure change

would take place during the early path of the solution while the pressure remained high, but rapid deposition should take place in the nearer surface low pressure region.

4) The hydrothermal solution is a liquid over the high pressure portion of its voyage, but boils, or expands, rapidly, owing to an approach to critical conditions somewhere in its path. In this case the history of the solution is marked by little ore deposition in the early deep part of its voyage, very rapid deposition or "dumping" in the zone where near critical phenomenon is shown or where boiling takes place, and little deposition over the rest of the journey.

All four types of solutions undoubtedly exist and certain criteria are available for distinguishing between them.

Geophysical Prospecting by the Use of Radioactivity Surveying

GERHARD HERZOG, The Texas Company, Bellaire, Texas

Pertinent factors relating to radioactivity surveying and particularly to aerial surveying are discussed.

Relationships of Radioactive Elements in Three Cores From the Gulf of Mexico

P. M. HURLEY, Massachusetts Institute of Technology, Cambridge, Mass.

Measurements of radium, emanating radon, manganese, iron, uranium, grain size distribution, and foraminifera are correlated in three cores from the deep part of the Gulf of Mexico. Manganese and radium vary together, and independently of the smaller changes of uranium content. Emanating radon follows variations in unsupported radium, and both appear to decay to low constant values below the upper 30 centimeters of core. No decay of ionium unsupported by uranium is apparent in the length of the cores, indicating that the total time involved is only a fraction of the half-life of ionium, but several half-lives of radium. The sediments have not been disturbed and are stratigraphically correlated over a distance of 200 miles.

The Amplitudes of P_n From Epicental Distances of 1° to 20°

PERRY BYERLY and B. TULLER, University of California, Berkeley, California

Several graduate students in the Seismographic Station in the University of California at Berkeley have in recent years made extensive measurements of the amplitudes of P_n waves recorded on Wood-Anderson seismographs at epicentral distances 1° to 20°. The difficulty in comparison lies in the fact that there are only a very few records of an individual earthquake and these frequently at distances which do not cover a large range. One is then forced to attempt to reduce the records of different earthquakes to some standard so that they can be compared. Several methods of attempting to do this have been tried. The results are so scattered it seems impossible to draw any conclusions as to variation of amplitude with distance. However, when individual earthquakes are studied, each covering only a short range of epicentral distance, there does seem to be some slight indication that near the epicenters the amplitudes die off, later to rise and then to fall again. Suggestions as to why this should be are offered.

Some Results of Wave Propagation From the Kern County Shock, July 21, 1952

B. GUTENBERG, California Institute of Technology, Pasadena, California

The longitudinal waves (P) and transverse waves (S) produced by the main shock of the Kern County, California, earthquake series exhibit shadow zones at epicentral distances from 6 to 16 degrees (for P) and to 20 degrees (for S) which are caused by a low velocity layer at depths between about 60 and 150 kilometers for P, and down to about 250 kilometers for S.

Distribution of compressions and dilatations in P and the angle of polarization in S permit the determination of the direction of faulting.

The amplitudes of the surface waves are about ten times as large in the direction in which faulting proceeded (northeast) than in the opposite direction.

Since the epicenter could be determined within a very few kilometers and the origin time within a few tenths of a second, the observed travel times can be used to improve the travel time curves now is use.

Exact Transient Solution of the Buried Line Source Problem

W. W. GARVIN, California Research Corporation, La Habra, California

The disturbance due to a line source buried within an elastic, homogeneous and isotropic half-space has long been one of the most challenging problems of seismology. Exact formal solutions have been published by a number of investigators, but the integrals which appeared in their solutions could be evaluated only approximately at large distances from the source. As a result, the behavior at intermediate distances or close to the epicenter could not be investigated analytically.

This paper discusses a new approach to the problem. It is shown that the use of Laplace Transform Techniques and of a suitable contour in the complex plane reduce the complexity of the problem to a point where no integration is required. The surface displacements as a function of time and position are found to be expressible in terms of algebraic functions in closed form. The case of a source displacement consisting of a sudden rise followed by a gradual recovery is considered in detail. Graphs are presented which show the vertical and horizontal surface displacement as a function of time, at different distances from the epicenter and for different values of Poisson's ratio.

A 3-Dimensional Seismic Wave Model With Both Electrical and Visual Observation of Waves

D. SILVERMAN, J. F. EVANS, C. F. HADLEY, and J. D. EISLER, Stanolind Oil and Gas Company, Tulsa, Oklahoma

A seismic wave model employing repetitive piezoelectric initiation and detection of ultrasonic pulses to give stationary oscilloscope patterns which are characteristic of the resulting transient wave motion is described. The design of a piezoelectric transducer assembly suitable for initiating or receiving single highly damped elastic pulses in a solid or a liquid will be given. Multi-trace records are produced with a single detector through the use of a simple photographic technique. An example is given showing reflections in a Plexiglass plate. Also, as an aid in wave identification in the model, traveling elastic wave fronts in transparent media have been rendered visually observable by means of stroboscopic illumination and either of two alternative optical techniques. Required circuits, including modifications of a radar transmitter necessary to produce electrical sparks in air sufficiently short and accurately enough timed to make compressional waves in Plexiglass plainly visible, are presented. As examples, photographs will be shown of the transformation of longitudinal waves into transverse by reflection within plastic blocks, as well as of the progressive advance of a wave front incident at grazing angle against a Plexiglass-liquid interface and refracted at the critical angle into the liquid.

Measurement of Elastic Wave Velocities in Stressed Solids

D. S. HUGHES, University of Texas, Austin, Texas

The variation of the velocity of both dilatational and rotational waves with hydrostatic pressure and temperature has been measured for several rocks and minerals at pressures up to several thousand bars and temperatures up to a few hundred degrees Centigrade. Since both velocities are measured, the elastic moduli, Poisson's ratio, and the density can be computed as functions of pressure and temperature. There are two possible sources of error in these computations: first, the adiabatic moduli are not identical with the isothermal and second, the measurements are made with high frequency pulses. The difference between the adiabatic and isothermal moduli is small and can be approximately computed. The possibility of the wave velocity being a function of frequency is not easily disposed of; such data as we have obtained indicate that this error is not greater than some two per cent.

The fact that the wave velocity is a function of pressure shows that the ordinary infinitesimal

or first order theory of elasticity is not applicable. The observed behavior of rocks under pressure appears to derive from two sources. In the low pressure range, up to about 2,000 bars, the velocity usually increases rapidly and non-linearly; above this pressure the velocity increases more slowly and linearly. The division between the two ranges is not well marked and can only be made qualitatively. The rapid non-linear increase is almost certainly due to closing up pore space in the rock. The slow linear increase is due to the non-linear elasticity at large strains. Actually, of course, both effects operate over the whole range. At low pressures the closing up of pore space is most important and at high pressures after the pore space is closed up the effects of the non-linear elasticity become apparent.

A 3-Dimensional Model for Seismic Studies

F. K. LEVIN* and H. HIBBARD, The Carter Oil Company, Tulsa, Oklahoma

Extensive programs designed to determine why some areas cannot at present be explored with the reflection seismograph have been reported by various oil companies; the work has been both experimental and theoretical in nature. Except for the very simplest subsurfaces, the theoretical calculations involved in these studies are so complicated that mathematical computers have been necessary.

The particular computer in use at the Carter Oil Company Laboratory is an analogue computer consisting of two beds of different solids, representing 250′ of sandstone over 83′ of limestone on a scale of 1′ of computer thickness to 1,000′ of earth.

With this computer, called the three-dimensional seismic model, the propagation of ultrasonic pulses along and through the beds has been investigated as a function of source-detector separation. Records obtained by photographing an oscilloscope face resembled greatly field seismographs. Among the events identified by comparison with theoretical time-distance plots were the direct dilatational and ground roll arrivals, the dilatational and shear reflections from the interface between beds, a refracted wave, shear-shear and shear-dilatational transmitted pulses.

The amplitude of the ground roll was found to fall off with distance approximately as the square root of the distance; this behavior is that expected for a Rayleigh wave. The amplitudes of selected cycles of an interbed reflection were found to peak sharply with increasing source-detector separation. A few investigations of the ability of linear detectors to reduce surface waves were undertaken. Work is continuing to develop fully the preliminary results reported here.

Seismic Model Studies

W. L. ROEVER, Shell Development Company, Houston, Texas

This is a report on some results of a seismic model program being conducted at the Shell E. and P. Research Laboratory in connection with fundamental studies of elastic wave propagation. The models are constructed of materials with low losses, so the assumption is made that the effects observed are primarily the result of geometry. The method used is essentially that of exploration seismology scaled down for use in the laboratory. The spark sources and electromagnetic and piezoelectric detectors used are described briefly. The first series of experiments discussed deals with propagation in a solid half-space. These results are compared qualitatively with theoretical results of Lamb.[1] The second series is concerned with propagation in a liquid layer overlying a solid. These results are compared with the theory developed by Pekeris[2] and Press and Ewing.[3] Although some of the results obtained to date have been encouraging, considerable difficulty has been experienced in interpreting

* On leave to Hudson Laboratories, Columbia University, Dobbs Ferry, New York.

[1] Lamb, H., "On the Propagation of Tremors over the Surface of an Elastic Solid," Phil. Trans. Roy. Soc., London A 203, 1, 1904.

[2] Pekeris, C. L., "Theory of Propagation of Sound in Shallow Water, in Sound Transmission in the Ocean," Mem. No. 27 Geol. Soc. Am., 1948.

[3] Press, F. and Ewing, M. "A Theory of Microseisms with Geologic Applications," Trans. Amer. Geophys. Union, Vol. 29, No. 2, April, 1948.

the results of supposedly simple laboratory experiments. These difficulties may be resolved when the elastic theory is worked out completely for the specific problems under investigation.

Filtering Associated with Selective Sampling of Geophysical Data

V. M. SOKOLOFF and C. A. SWARTZ, United Geophysical Company, Pasadena, California

Selective sampling of geophysical observations is a common procedure employed in the mass treatment of this type of data.

Simple running averages, weighted running averages, and derivatives are a few examples of selective sampling techniques applied to a single series of observations. The filtering action of these computations as a function of periodicities can be represented quantitatively by means of filter curves.

Data which are recorded electrically, as for instance, on magnetic tapes, are especially susceptible to sampling methods. In this case more complicated computational operations such as auto-correlations, cross-correlations and continuous predictions can be accomplished electronically.

So-called residual maps are often prepared from observational data presented in contoured map form. This is particularly true for gravity and magnetic data. These residual maps are usually computed by taking running two-dimensional pattern samples of neighboring values, and may be considered to be filtered versions of the original map. The two-dimensional selective or filtering effects of such residual processes may readily be given quantitative representation.

The several traces on a seismic record afford an example of data in a form which can be subjected advantageously to running combinations, predictions, auto-correlations and cross-correlations.

Examples of a number of typical operations, of the types discussed above, will be given and their effects on the original data will be discussed.

Statistical Analysis of Seismic Records

G. WADSWORTH, Massachusetts Institute of Technology, Boston, Massachusetts

An Approximate Method of Interpretation in Resistivity Prospecting

C. L. PEKERIS, Weizmann Institute of Science, Rehovot, Israel

It is shown that, as a first approximation, the conductivity function can be represented as a solution of an integral equation of the Laplace type. Some examples of the use of this method will be given.

Dynamos and Terrestrial Magnetism

E. C. BULLARD, National Physical Laboratory, Teddington, England

Solution of Electrical Prospecting Problems by Means of a Metallic Model

W. J. YOST and R. L. CALDWELL, Magnolia Petroleum Company, Dallas, Texas

A metallic model for use in low-frequency electrical exploration has recently been described (GEOPHYSICS, Volume 17, p. 806, October, 1952). In such a model the electrical resistivity is used as the scaling parameter. Consequently, the same type of pulsing or frequency operation can be used in both the model and field applications. Methods for obtaining response curves in idealized situations are described. Also a scheme for using the model directly in field applications is illustrated. In order to cover the required range of resistivities it is necessary to modify the bulk resistivity of some of the metals used. Finally, an interpretation of the results in terms of image signals is presented as an aid for the geophysicist.

Estimation of Spectral Distribution of Incoming Short and Long Wave Radiation by Non-Refractive Radiometer

F. A. BROOKS and C. F. KELLY, University of California, Davis, California

A Fundamental Seismic Research Program

DANIEL SILVERMAN, Stanolind Oil and Gas Company, Tulsa, Oklahoma

The seismic process may be considered as a complex communication system which may conveniently be divided for study purposes into three zones, namely, the initiation, transmission, and receiving zones. A seismic impulse generated in the initiation zone is propagated by a multitude of paths through the transmission zone, and is suitably detected in the receiving zone. The fundamental seismic research program to be described can thus be conveniently divided into three related portions, each of which is concerned with one of the three zones. Each portion of the program is further subdivided into various investigational topics.

The program of research dealing with the various topics in the initiation zone involves experimental and theoretical studies of the pressure fields and wave shapes in the vicinity of exploding charges of various kinds and configurations. The research topics dealing with the transmission zone involve both full-scale field and laboratory model experiments related to the generation and transmission of bound and body waves through stratified media. This program also includes theoretical studies of wave propagation in stratified media. Topics dealing with the receiving zone include the effects of frequency, filtering, and other physical operations on seismic time functions, and mathematical investigation on the application of information theory to the improvement of seismic data in general and signal-to-noise ratio in particular. In describing this comprehensive research program, examples will be given of work carried on in each of the above fields.

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The Executive Committee has approved for publication the names of the following candidates for membership in the society. This publication does not constitute an election but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees he should send it to the president within thirty days. Names of the references appear in parentheses after the name of each nominee.

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George Harold McDade (J. H. Frasher, Robert A. Boulware, C. E. Patton)
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Don Russell Mabey (H. V. W. Donohoo, Kenneth L. Cook, Henry R. Joesting)
Duncan Donald MacAskill (R. B. Oldaker, R. E. Doe, F. A. Hale)
Joe Malendez (Dean Walling, V. E. Prestine, Aart deJong)
Kermont Burdell Mickelson (R. M. Bradley, E. J. Gemmill, H. B. Ericson)
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Eugene Girden Mugrage (Frank J. Rollins, Martin C. Kelsey, Henry C. Towles, Jr.)
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Richie Ellsworth Boatman (Karl Dyk, L. D. Ervin, Howard Itten)
Arthur Roy Clark (E. Westrick, D. J. Salt, S. H. Ward)
Lewis Frederick Judson (J. B. Nicholls, W. Omer Clark, S. D. Rogers)
Kuniyuki Katayose (Kumiji Iida)
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SEVENTH ANNUAL MIDWESTERN MEETING
DALLAS, TEXAS
NOVEMBER 12–13, 1953

Sponsored by the six midwestern local sections of the Society of Exploration Geophysicists, the Seventh Annual Midwestern Meeting was arranged and directed by members of the Permian Basin Geophysical Society, Midland, Texas. The other participating sections were Ark-La-Tex Geophysical Society (Shreveport, Louisiana), Dallas Geophysical Society, Fort Worth Geophysical Society, Geophysical Society of Oklahoma City, and Geophysical Society of Tulsa. The Adolphus Hotel in Dallas, Texas, was headquarters for the 835 delegates. Five technical sessions were conducted in the Ballroom of the Adolphus, the following members serving as chairmen: W. D. Baird, R. B. Baum, John M. Crawford, C. G. Dahm, Milton B. Dobrin, Norman H. Ricker, L. O. Seaman, and L. H. Wells.

General Chairmen of the meeting were R. M. NUGENT and L. H. JOHNSON, of Midland, who

directed activities of the following committees:

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P. CONNOR, Shreveport

PAPERS PRESENTED AT THE SEVENTH ANNUAL MIDWESTERN MEETING

Opening of Meeting

GEORGE A. GRIMM, President of Permian Basin Geophysical Society. Tide Water Associated Oil Company, Midland Texas

Our Expanding Horizons

ROY L. LAY, President of the Society of Exploration Geophysicists. The Texas Company, Houston, Texas

Current Status of Marine Exploration

CURTIS H. JOHNSON, Geophysical Service Incorporated, Dallas, Texas

Marine exploration for oil is expanding and promises to expand further, even though land exploration may be in a period of adjustment. Political weather is favorable for such expansion; geological factors are highly promising and continued maintenance of reserves demands such expansion. Technical advances in the art of marine exploration and in marine drilling make such expansion logical and feasible.

A Study of Wave Motion in the Elastic Region Near the Shotpoint

FRANK TROSETH, Magnolia Petroleum Company, Midland, Texas

An understanding of the mechanics by which elastic waves are initiated in rocks is a primary aim of basic seismic research. Much of the experimental work done on the subject has been inconclusive because the investigators found it necessary to assume a "probable" pressure distribution on the surface between regions of elastic and non-elastic deformation.

A mathematical analysis of wave propagation indicates that the assuming of a pressure distribution may be avoided by making measurements in the elastic region surrounding a shotpoint and

extrapolating the information gained back to the desired surface. Experimental studies of wave propagation in a large tank of pitch show that the mathematical method of extrapolating measured information from one point to another in an elastic medium can be applied to an actual physical system.

Capitalization of Exploration Expense

KENNETH G. MILLER, Arthur Young and Company, Houston, Texas

This paper discusses the problem of the treatment for federal income tax purposes of geophysical and geological expenditures.

The history of the deductibility vs. the non-deductibility of these costs, as well as the current attitude of many industry representatives, is described.

Notes on the Use of Multiple Geophones

LEONARD V. LOMBARDI, Gulf Oil Corporation, Fort Worth, Texas

The use of multiple geophones, which has been largely empirical, serves two primary functions: cancellation of random and other unwanted energies, and improved sampling of the wave front. Curves are presented showing surface-wave-cancellation effectiveness of several different spreads. The results also apply to mixed records. Cancellation of random energies follows conventional sampling theory, varying with the square root of the number of geophones in the spread. Sampling of the wave front is more complex because the samples are not mutually independent.

Problems in the Application of Transistors to Seismic Equipment

R. W. OLSON, Texas Instruments Incorporated

Brief general theory of operation of transistors, movement of current carriers through crystal lattices, limits to vacuum tube analogy, circuit elements, parameters, amplifier configurations, performance characteristics and possibilities, and future possibilities are discussed.

Geophysical Management Looks at Safety as a Public Relations Factor

CECIL H. GREEN, Geophysical Service Inc., Dallas, Texas

The public relations value of a good safety program is stressed. Public relations is not something that can be turned on and off at will—every company in every industry has it—whether it is wanted or not.

It has only recently become clearly appreciated that every safety activity has public relations value—good or bad. Just doing a good job on safety isn't enough; the job is not completed until the public and clients are made aware of the fact.

A worthy objective of safety then should be to create the most favorable human relations possible. The prevention of accidents by increasing safety activity within the industry is but one of the factors leading to betterment of public and employee relations within the geophysical exploration industry.

Correlation Between Surface and Subsurface Section of the Ellenburger Group of Texas

LEO HENDRICKS, Texas Christian University, Fort Worth, Texas

The nature and stratigraphic occurrence of the Ellenburger group of Texas as now defined in the areas of its outcrops are discussed. An understanding of the occurrence of the Ellenburger formation in the subsurface involves the use of dependable correlative criteria common to both outcrop and subsurface data. Grain size and insoluble residues appear to offer the best means of correlation, and a description is made of the acquisition and study of residues from surface sections. Recognition of the Ellenburger in the subsurface by a study of gross lithology is discussed. Lithologic and residual characteristics of the five formations of the Ellenburger group are described. Correlation of Ellen-

burger subsurface sections with surface sections is made, largely on the basis of evidence on residue logs. The paper is concluded with a systematic discussion of insoluble residues.

Pressure Field Around Distributed Charges

N. R. SPARKS and DANIEL SILVERMAN, Stanolind Oil and Gas Company, Tulsa, Oklahoma

The pressure field in the earth around a long continuous vertically distributed charge depends primarily upon the velocity of detonation of the explosive. When the detonation velocity matches the velocity of the surrounding formations, the initial pressure is most intense in the direction of detonation and may be 20 to 30 times the pressure in the opposite direction and to the side of the charge. This pressure ratio falls to approximately 6:1 when the detonation velocity is 20% higher or lower than the formation velocity. Matched velocity charges exhibit strong directional characteristics with respect to reflection as well as with respect to pressures in the vicinity of the charge.

Seismic Wave Types in a Shallow Bore Hole

EMMET D. RIGGS, The Atlantic Refining Company, Dallas, Texas

Field measurements of near surface velocity, using a multiple seismometer array within the bore hole, indicates the presence of a well developed secondary event. This type of wave has been generated under controlled conditions and from its characteristics identified as an interface type, generally known as a bound tube wave. Some practical aspects of near surface velocity surveys and up-hole measurements are considered.

Propagation of Radio Frequency Energy Through the Earth

F. M. MCGEHEE, United Gas Corporation, Shreveport, Louisiana

The results of measurements of some propagation characteristics of 1614 and 1700 kc radiation through the earth are reported. In experiments conducted at Carlsbad Caverns, N. M., and Mammoth Cave, Ky., transmitters were set up on the surface 700 and 280 feet above unwired tunnels, and the signal strength measured at many points in the tunnels. The data are interpreted to show that the radiation is approximately equal over an underground hemisphere and that the attenuation is about 0.014 and 0.05 to 0.1 nepers/meter at the two locations respectively. These values are in good agreement with theory.

A Talk and Demonstration of Poisonous Snakes, Their Habits; the Hazards and Treatment of Bites

SPONSORED BY MEDICAL SUPPLY COMPANY, Rockford, Illinois

An Illustrated Talk on Poisonous Plants; Their Identity, and the Prevention and Treatment of Poisonous Plant Dermatitis

EARL LOFTUS, M. D., Dallas, Texas

A Demonstration of the Generation of Static Electricity on Human Beings and Field Equipment, and Its Hazards to the Users of Electric Blasting Caps

G. M. KINTZ, Chief, Accident Prevention and Health Division, Region VI, Bureau of Mines, Dallas, Texas

Geophysics as a Geological Tool

JOHN EMERY ADAMS, President of The American Association of Petroleum Geologists. Standard Oil Company of Texas, Midland, Texas

Analysis of Potential Fields

L. L. NETTLETON, Gravity Meter Exploration Company, Houston, Texas

Geophysical measurements of potential fields (i.e. the gravity and magnetic methods) include the sum of all effects below the level of measurement. The separation of these into regional and

residual components is a basic problem in the interpretation of such measurements. We have no definite criterion for a "correct" regional because the source of potential fields is ambiguous. It is shown that the several analytical and mathematical or "grid" systems do not provide such criterion because of choices or assumptions which must be made at certain steps in the derivation of the numerical factors by which such systems are reduced to practice. Several of the published systems are compared with each other and with a graphical residual system by a table of relative weights of their coefficients and by application to the same map.

In spite of the limitations and empirical nature of any method of determining a regional it is possible to make very effective use of one or more approaches to the regional problem. An understanding of the possibilities and limitations of the several possible methods is necessary for the proper application and for any interpretation of the resulting "anomalies."

Time Method of Migrating Steep Dips

R. B. RICE, Phillips Petroleum Company, Bartlesville, Oklahoma

The purpose of this paper is to present a time-resolution method of performing reflection seismograph computations which is particularly useful in steep-dip areas. Two of the principal advantages of the method are that it is simple and fast to use and that it allows the use of any desired velocity gradient or the rapid change from one velocity function to another. In addition, examples of actual cross sections computed by this method are presented.

Lower Cretaceous Stratigraphy of Mississippi

J. D. NUNNALY and H. F. FOWLER, Gulf Refining Company, Shreveport, Louisiana

The Lower Cretaceous of Mississippi occurs only in the subsurface. It is composed of the Comanche series alone, or of the combined Comanche series and Coahuila series. In southern Mississippi, some Lower Cretaceous groups and formations can be recognized, on electric logs and by lithologic characteristics, as being equivalent to units in Louisiana where the stratigraphic sequence is more firmly established. Key beds of the Lower Cretaceous of southern Mississippi are the Washita and Fredericksburg limestones and the Ferry Lake anhydrite. The Ferry Lake anhydrite was not deposited northeast of a line from central Issaquena County to northeast Greene County. Washita and Fredericksburg limestones are not present north of a line between Claiborne County and Greene County. North of this line Washita and Fredericksburg rocks are clastic, and are difficult to recognize because of the absence of limestones and the lithologic similarity between them and the overlying and underlying strata. Eight structures in Mississippi have produced oil or gas from Lower Cretaceous sediments. Reservoir rocks and good structures exist in Mississippi and additional Lower Cretaceous exploration is justified.

Review of Pattern Shooting

A. E. MCKAY, Continental Geophysical Company, Fort Worth, Texas

Patterns of shot holes and patterns of seismometers are now standard technique in many areas currently being surveyed by seismograph. This paper reviews some of these pattern arrangements and shows comparison records in a number of areas such as New Mexico, West Texas, western Oklahoma, Mississippi, and others. Pattern shooting is a useful technique but is by no means a cure-all.

A Brief Summary of Three Years of Seismic Field Research

J. W. HAMMOND and H. M. THRALLS, Seismograph Service Corporation, Tulsa, Oklahoma

The first objective of a seismograph field research unit is to determine a procedure which will hold constant all variables except the one being investigated. The results of field research are, in a large measure, dependent on the attainment of this objective. Given proper instrumentation the competent field research engineer can reach conclusions and develop solutions if positive control over variables is established.

Field research, like other research, must be divorced completely from the "rush" and "push" of a commercial survey. Efficiency is highly desirable but cost per unit of subsurface coverage is of no importance during the research period.

The paper outlines the factors to be considered in a field research program and describes in brief some of the results obtained in three years of field operation in various localities of North America.

The Third and Fourth Dimensions in Exploration

JOHN DALY, Midland, Texas

The trend in exploration toward the investigation of deeper and geologically more complex structures necessitates a keener appreciation of the three-dimensional factors involved in evaluating them. For the deep structures where dips of from 5° to 10° are common, it is necessary to migrate the dips to their true position. A discussion of dip migration, what it is, why it is necessary, and the benefits derived therefrom, is given. The necessity of migrating dips in connection with fault problems is emphasized. Shooting techniques to improve the treatment of reflected events as a three dimensional problem are suggested.

Some of the geological prejudices concerning deep seated faults in the West Texas-New Mexico area which the writer has encountered are enumerated. A shooting picture can be correct geometrically and still not appear geologically sound until a fourth dimension has been added.

The close cooperation between the geologist and the geophysicist is emphasized as an economic necessity.

An Evaluation of the MicroLaterolog and MicroLog for Determining Formation Resistivity Factors

HAROLD D. SMITH and HAROLD A. BLUM, The Atlantic Refining Company, Dallas, Texas

A comparison of MicroLaterolog and MicroLog for determining formation resistivity factors indicates that the MicroLaterolog is significantly more accurate. The use of the MicroLaterolog in quantitative log interpretation will increase the value of electric logging as an exploration tool. Data supporting these conclusions are presented comparing measured formation resistivity factors from cores with calculated values from the MicroLaterolog and MicroLog in both hard and soft rock country.

The Electrical Aspects of Connecting Geophones in Multiple

LOUIS W. ERATH, Industrial Electronics Company, Houston, Texas

This paper will discuss, broadly, electrical problems of impedance matching between geophones and input circuits of geophysical amplifiers. It will deal more specifically with the effect on energy transfer, frequency response, and damping of using a large number of geophones. Response curves and circuit diagrams will be furnished the audience in the form of a printed leaflet. No reference will be made to the seismic considerations of using geophones in multiple.

Different Basic Assumptions for Weathering Corrections

E. J. HANDLEY, Midwestern Geophysical Laboratory, Tulsa, Oklahoma

The mathematical computations involved in making weathering corrections are commonly based on the assumption that the near-surface sedimentary rocks are stratified into rather well defined "layers," with velocities of longitudinal seismic waves being considered as a *constant* for each layer. The basic data used in making weathering corrections are the measured values for first arrival refraction times and distances, and up-hole times and depths. It is shown that the assumption can be made that the velocity continuously increases with depth, and that when layers occur, they may be considered zones in which the velocity increases at indifferent rates. It is pointed out that the basic data may fit such assumptions equally well. The assumption by Blondeau that the velocity $V_z = CZ^{1/n}$ is discussed and some of the mathematical relationships involved are shown to be so simple that they can easily be applied to making weathering corrections.

PACIFIC COAST REGIONAL MEETING
LOS ANGELES, CALIFORNIA
NOVEMBER 5–6, 1953

The Annual Meeting of the Pacific Coast Section of the Society of Exploration Geophysicists was held jointly with those of the Pacific Sections of The American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists at the Biltmore Hotel. Also cooperating was the University of California at Los Angeles Institute of Geophysics in holding its Technical Conference on the university campus. Chairmen of SEG sessions were L. B. Slichter, Robert B. Galeski, Carl H. Savit, and W. D. Cortright.

Melvin J. Hill was General Chairman, directing the activities of the following convention committees:

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G. Y. WHEATLEY

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J. C. BENZLEY
M. C. BORN
W. R. WHITE

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C. H. SAVIT

PUBLICITY

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L. H. METZNER

REGISTRATION

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PAPERS PRESENTED AT THE PACIFIC COAST MEETING

Our Expanding Horizons

ROY L. LAY, Manager of the Geophysical Division, The Texas Company, Houston, National President, SEG.

The Microlog Continuous Dipmeter

PIERRE DE CHAMBRIER; presented by CHARLES F. GALLAGHER, Schlumberger Well Surveying Corporation, Bakersfield

Some of the methods used at the present time for the determination of the angle and of the azimuth of the dip of the formations traversed by a bore hole are based on the correlations between three curves recording certain electrical characteristics of the formations, such as SP or resistivity, along the wall of the bore hole in three equally spaced azimuths. With the conventional equipment used for the application of these methods, the measurements are made over separate intervals of depth.

In the present paper, a new improved instrument called MicroLog Continuous Dipmeter is described, wherein the three curves used for the determination of the dip are obtained with three MicroLog devices, and wherein these three dipmeter curves,—and furthermore the orientation of the instrument and the inclination of the bore hole—are simultaneously and continuously recorded.

It is shown that, with the help of this instrument, more numerous dip determinations can be made in a given well, with a higher accuracy and a greater recording speed.

The paper is illustrated with field examples.

Geophysical History of South Cuyama Oil Field, Santa Barbara County, California

JOHN W. MATHEWS, Richfield Oil Corporation, Bakersfield

In the course of a regional seismograph survey an anticlinal dip reversal was obtained in the foothill topography on the south side of Cuyama Valley, California. Further investigation of this significant anomaly led to the mapping of an anticline closed on three sides with indications of the presence of faulting on the fourth side to aid in creating a trap. On the basis of this information a test well was drilled which resulted in the discovery of the South Cuyama oil field May 4, 1949. Slides will be shown on the key seismograph cross sections and some of the difficulties of the work discussed. The original seismograph contour map as well as the map drawn from well data will be shown to enable an evaluation of the seismograph prediction. As of June 30, 1953, the field contained 235 producing wells and had a cumulative production of 44,172,749 barrels of oil and 29,312,888 Mcf of gas.

Case History of Wild Goose Gas Field, Butte County, California

WALLACE L. MATJASIC, Honolulu Oil Corporation, Bakersfield

The discovery well of the Wild Goose gas field was drilled and completed in 1951 on a structure located by a reflection seismograph survey conducted in 1950. An additional seismograph survey was made subsequent to discovery to define better the structure for future development. Two seismic cross sections and a contour map based on the original reflection data are shown, along with an aeromagnetic map which was made after the discovery.

The producing sands are in an interval between the Forbes shale of upper Cretaceous age and the overlying Capay shale of Eocene age.

Radioactivity Measurements in Los Angeles Basin

H. WAYNE HOYLMAN and W. L. MORRIS, Hoylman-Morris Consultants, Los Angeles

The paper discusses some of the results obtained during the past two years from gamma radiation surveys which have been studied as geophysical data reflecting certain geological conditions. The problem of determining gamma ray anomalies with a continuous recording scintillation counter is discussed. Cross sections and contour maps will be shown of gamma radiation measurements, on the ground and in the air, across certain oil fields and geological structures in the Los Angeles Basin. Some correlations of radioactivity and aeromagnetics with geology will be shown.

One-Dimensional Transducers for Seismic Models

L. KNOPOFF and G. L. BROWN, Institute of Geophysics, University of California, Los Angeles

The surface excitation of seismic models imposes certain conditions upon the nature of the source and receiving transducers to be used. Among these conditions are those of size, stability, directivity, adaptability, and efficiency. The present investigation determines the physical properties of transducer materials most ideally suited for use in seismic models and the proper use of these materials in the production of pressure pulses of the desired type and in the detection of the resultant motion. As an example of the several types of electro-mechanical transducer materials, attention is limited to the class exhibiting elastic, piezoelectric properties. The conditions of adaptability and stability in a one-dimensional source are satisfied by a suitable choice of source material, excitation wave form, and load impedance. One-dimensional receivers may be selected by an appropriate choice of piezoelectric material, size, and load impedance. An indication is made of the techniques employed for a solution

to the three-dimensional problem. Materials possessing properties satisfying a large number of the one- and three-dimensional conditions are described.

Observed Mohorovicic Reflections in Blasts and Local Earthquakes

GEORGE G. SHOR, JR., Seismological Laboratory, California Institute of Technology, Pasadena

Seismograph records of large blasts at three different points in Southern California show a reflection arriving between 10 and 11 seconds double vertical time, which is probably a reflection from the Mohorovicic discontinuity—the base of the continental layer. The corresponding refracted wave from these and other blasts shows an intercept time of 8 seconds. With the values obtained for each of these blasts and using velocities obtained from blasts and local earthquakes, a crustal thickness of about 30 kilometers (19 miles) is obtained in the neighborhood of all three blasts.

Blast recordings at more distant points have given tentative reflection travel-time curves, which are being used in conjunction with similar data obtained from earthquake records to study variations in depth of the Mohorovicic discontinuity and in focal depths of the earthquakes.

Safety—A Responsibility of Management

CARL H. GERDES, Western Geophysical Co. of America, Los Angeles

Management must accept full responsibility for the task of eliminating preventable accidents. This can be accomplished by a well organized, efficient safety program. The program should be planned and executed so that it will arouse the individual worker's interest as well as the competitive spirit of the entire field party. To some extent, awards should be given for exceptionally good safety records. The safe physical condition of the field equipment is also the responsibility of management. An active safety committee, composed of top management executives at the head office should conduct regular meetings to review all accidents that occur in the field and to formulate the company policy on safety.

Recording of Seismic Waves in Bore Holes

E. T. HOWES, United Geophysical Company, Pasadena

Reflected and refracted seismic waves are normally detected by a "horizontal spread" of geophones placed at the surface of the ground. However, these same seismic waves can be detected by a "vertical spread" of geophones suspended in a fluid-filled bore hole. Equipment specially designed for use as a vertical spread in shallow bore holes is described in this paper.

Sample records taken under various field conditions are shown. The relative advantages and operating problems are also discussed.

Similar equipment designed to withstand high pressure and temperature of deep bore holes and suitable for velocity surveys and other purposes is also described.

Forces and Effects of Explosives in Submarine Geophysical Exploration

F. J. HORTIG, State Lands Commission, State of California, Los Angeles

Normal application of explosions as the requisite point source of high-intensity low-frequency energy in submarine geophysical exploration has necessitated controls on steepness of pressure wave front and peak pressure amplitude to minimize damage to marine life and eliminate contended damage to marine and onshore physical structures.

Limited quantitative measurements have been made of the forces and effects of "jet" and "open" submarine shots on marine and onshore physical structures to permit establishment of practical operating control limits. In addition, measurements of force amplitudes and effects resulting from railroad and highway transportation were made for comparison with the effects of geophysical explosions at comparable measurement distances. Concurrent observations and analyses of damage to marine life were also conducted.

Highlights of Seismic Exploration in California

MAURICE SKLAR, Union Oil Company of California, Bakersfield

The history and development of seismic exploration in California is reviewed, from its beginning in the 1920's to the present day. The refraction and reflection methods have both been used, but the latter has proved to be more effective in discovering petroleum. The earliest reflection technique employed the "correlation" method. This was replaced by the "dip" method, and later by "continuous profiling."

Those oil and gas fields whose discovery can be credited at least in part to the seismograph are indicated. They are grouped in four periods, which are mainly chronological, but partly geographical. These are (1) Early gas discoveries (1931–1936); (2) Southern San Joaquin Valley oil discoveries (1936–1944); (3) Sacramento Valley gas discoveries (1937-present time); (4) Recent period of California oil discoveries (1946–present time).

Quite often seismic parties exploring for petroleum record earthquakes. An excellent example is offered by the Kern County shocks of July and August, 1952. Three seismograms, recorded by a seismic party working within a few miles of the White Wolf fault, show earthquake events. These events are discussed, and related to aftershocks recorded by earthquake stations.

Reflections on Some Hypotheses of Mountain Building (Invited Address)

DAVID GRIGGS, Institute of Geophysics of the University of California, Los Angeles

The speaker discusses the adequacy of the contraction hypothesis presented in an SEG Distinguished Lecture Tour by J. Tuzo Wilson, using a new approach to the problem. He reviews the recent arguments for and against the theory of crustal convection. He also discusses the implications of heat flow measurements in the Pacific by Scripps and Rubey's theories of continental growth by selective fusion of the mantle.

A speculative mechanism is advanced for auto-catalytic formation of continents and a new mechanism contributory to mountain building.

EASTERN REGIONAL MEETING
BOSTON, MASSACHUSETTS
DECEMBER 29, 1953

Under the chairmanship of L. Don Leet, the Eastern Regional Meeting was held at Hotel Somerset, Boston, concurrently with the Annual Meeting of the American Association for the Advancement of Science. R. B. Ross, Chairman of the Eastern Region Program Committee, assisted by Frank Press, was in charge of program. R. F. Beers, SEG Representative on the AAAS Council, arranged for holding the meeting concurrent with that of the AAAS, with all facilities furnished by the AAAS. This was the first joint meeting of the two organizations since their affiliation. Francis Birch and R. F. Beers presided.

PAPERS PRESENTED AT THE EASTERN REGIONAL MEETING

The Ionium Method of Age Determination—Recent Developments

HERBERT L. VOLCHOK, Lamont Geological Observatory, Columbia University, New York and J. LAURENCE KULP, Associate Professor of Geology, Lamont Geological Observatory, Columbia University, New York

The Ionium Method of age determination is based on the lack of equilibrium in the series Uranium, Ionium and Radium of freshly deposited sediments of the deep sea. The relative concentrations of these elements approach equilibrium ratios with time after deposition, thus a curve of radium concentration as a function of depth in the core should exhibit a shape in accordance with known radioactive equilibrium theory. The most reliable dates appear to be obtained from cores homogeneous in sediment type and uniform in their depositional rate.

Surface area measurements have been made on the material of two cores dated by the Ionium Method. The results point to adsorption as the mechanism of ionium enrichment. In the case of the "ideal" core, the surface area was found to be relatively constant throughout its length. The second core which exhibits anomalous concentrations of radium at several depths was found to have a direct relationship between radium and surface area in the upper, youngest section.

Since the theory of the Ionium Method is concerned only with ionium derived from the ocean water, any ionium contained within the rock particles prior to its oceanic deposition is in excess, and will cause further anomalies in the radium-depth curve. Therefore, studies of the ratio of adsorbed to total radium of the core material are now in progress. It is hoped that quantitative measurements of this ratio will permit ionium dating of cores not previously useable.

Engineering Applications of the Seismic Refraction Method

REVEREND DANIEL LINEHAN, S.J., Director, Weston Observatory, Weston, Massachusetts

The applications of the seismic refraction method to engineering problems in northeastern United States have been many and varied. The uses of seismology in determining the location and design of highways; foundations for bridges, dams, and buildings; the location of construction materials, such as gravels, sands, and hard rock; the location of underground water supplies for communities and many other applications have been solved easily and quickly by the seismic refraction method. These studies have been made both on land and under water.

The present paper demonstrates the varied applications to which the author has subjected the method including underwater studies, both deep and shallow, and the application of the method to assist the archeologist.

Review of the Development of the Air-borne Magnetometer

ROLAND F. BEERS, Beers and Heroy, Dallas, Texas and DONALD E. BURNHAM, Rensselaer Polytechnic Institute, Troy, New York

Equations are developed for the general form of expression of the total intensity of the earth's magnetic field as measured by the airborne magnetometer. Existing models of magnetometers are examined to reveal the special cases which they represent in terms of the general equations. The examples selected include significant references published in the periodical and patent literature.

The Application of Geophysical Methods in New Brunswick

S. H. WARD, Executive Vice-President, McPhar Geophysics Limited, Toronto, Canada

A brief discussion concerning the applicability and limitations of several geophysical methods in New Brunswick is presented. An assessment is given of the use of the airborne magnetic, ground magnetic, electromagnetic, electrical resistivity, self-potential, and geochemical methods in the exploration for economic deposits of sulphide mineralization. A general discussion of the future applications of geophysical techniques in New Brunswick concludes the article.

Reconnaissance Geochemical Surveys for Base Metal Mineralization Carried Out in Lemieux Township, Gaspe Peninsula, Quebec

JOHN E. RIDDELL, Assistant Professor, Department of Geological Sciences, McGill University, Montreal, Canada. (*Presented with permission of the deputy minister of the department of mines of the Province of Quebec*)

During the field season of 1953, geochemical soil and water surveys were employed to outline zones of mineralization containing base metals, in a selected portion of Lemieux township of about 20 square miles in extent.

This area is located in a maturely dissected upland region, underlain by moderately folded and faulted Paleozoic sediments and volcanics which have been intruded by acidic and basic igneous

formations of Devonian age. The known base-metal mineralization is confined to quartz-carbonate veins carrying sphalerite, galena, chalcopyrite and pyrite.

Soil samples were taken at the base of side slopes along the valleys. These samples were analyzed for their content of readily soluble copper, lead, and zinc using standard laboratory procedures.

Water samples were taken at appropriate intervals along the main streams and their tributaries. These samples were analyzed in the field using a modified monocolor technique with dithizone as a reagent.

The results of the geochemical surveys show that both soil and water contain greatly increased amounts of base metals in the vicinity of the known showings. The areal distribution of the geochemical anomalies indicates that base metallization has been confined to a limited portion of the area surveyed.

Iron and Titanium Oxide Minerals of Adirondack Rocks and Their Magnetic Properties

J. R. Balsley, Geophysicist, USGS, Washington, D. C. and A. F. Buddington, Geologist, USGS, Princeton, New Jersey

Rocks from the northwestern Adirondack Mountains, New York that contain members of the hematite-ilmenite series intermediate between 6 and 95 percent hematite and intermediate members of the Fe_2O_3, $FeO \cdot TiO_2$ series with up to at least 15 percent TiO_2 (rutile) uniformly have reverse remanent magnetism. Intermediate members of the hematite-ilmenite series occur alone as accessory minerals over large areas and uniformly give rise to intense negative magnetic anomalies. Where magnetite and members of the hematite-ilmenite series occur together in different ratios, the magnetic properties are such as to indicate normal remanent magnetism for the grains of magnetite and reverse remanent magnetism for the associated grains of the hematite-ilmenite series.

When specimens of Adirondack rocks containing members of the hematite-ilmenite series are demagnetized by heating above the Curie point and are then cooled in a magnetic field they possess remanent magnetism opposite in direction to that of the magnetic field.

It is tentatively concluded that the reverse remanent magnetization of these rocks and the attendant negative anomalies are caused by the inherent properties of the intermediate members of the hematite-ilmenite series which they contain.

Experiments to determine the mechanism by which these minerals develop reverse remanent magnetization are continuing.

A Brief Summary of Three Years of Seismic Field Research

J. W. Hammond, Senior Research Engineer, Seismograph Service Corp., Tulsa, Oklahoma and H. M. Thralls, Vice-President, Seismograph Service Corp., Tulsa, Oklahoma

The first objective of a seismograph field research unit is to determine a procedure which will hold constant all variables except the one being investigated. The results of field research are, in a large measure, dependent on the attainment of this objective. Given proper instrumentation and choice of instrumentation the competent field research engineer can reach conclusions and develop solutions if positive control over variables is established.

Field research, like other research, must be divorced completely from the "rush" and "push" of a commercial survey. Efficiency is highly desirable but cost per unit of subsurface coverage is of no importance during the research period.

The paper outlines the factors to be considered in a field research program and describes in brief some of the results obtained in three years of field operation in various localities of North America.

Vertical Gravity Gradient in San Jacinto Monument, Texas

Sigmund Hammer, Head, Gravity Interpretation Section, Gulf Research & Development Company, Pittsburgh, Pennsylvania and E. H. Farr, Geophysicist, Gulf Research & Development Company, Pittsburgh, Pennsylvania

Precise determinations of the vertical gradient of gravity have been made in few places on the

earth. A recent set of gravity measurements with a modern high-sensitivity Worden gravimeter over the 558-foot elevation range in the San Jacinto Monument near Houston, Texas, yields a new determination. The gravity differences were measured to a precision of about ± 0.05 milligals (5×10^{-5} cgs.). Necessary corrections for gravitational effects of the masses in the Monument and adjacent topography have been applied. The results are of interest in the fields of geodesy and exploration geophysics.

Evaluation of Linear Operators in Seismogram Analysis

ENDERS A. ROBINSON, Director, Geophysical Analysis Group, Department of Geology and Geophysics, Massachusetts Institute of Technology, Cambridge, Massachusetts

The usefulness of linear operators in the analysis of seismograms is dependent among other considerations on geologic and mathematical limitations.

Certain of the more significant limitations will be discussed and illustrative examples on seismic records will be presented.

Energy Distribution in Explosion-Generated Seismic Pulses

B. F. HOWELL, JR., Associate Professor of Geophysics, School of Mineral Industries, The Pennsylvania State University, State College, Pennsylvania and D. BUDENSTEIN, United States Geological Survey

Three separate pulses were recognized on a group of seismograms of ground motion resulting from explosions measured at distances ranging from 10 to 1,172 feet from the shotpoint. It is believed that the first pulse represents primarily body waves, the second pulse coupled waves formed by internal reflections in the low-velocity surface layer, and the third pulse Rayleigh and Love waves arriving simultaneously. The ratios of the energies of the various pulses are given for several distances. The rates of attenuation of the three pulses are expressed as exponential functions and also as inverse power functions.

Airborne Magnetometer Profile from Portland, Oregon to Albuquerque, New Mexico

W. B. AGOCS, J. C. ROLLINS, and E. BANGS, Geophysicists, Aero Service Corporation, Philadelphia, Pennsylvania

An airborne magnetometer profile of the variations of the earth's anomalous total magnetic field was obtained using a wing-tip magnetometer installation in flying a course from Portland, Oregon to Albuquerque, New Mexico. The magnetic data were obtained by flying at barometric altitudes ranging from 7,000 to 10,000 feet above mean sea-level.

The variations in the total magnetic field are tied to the known geology along the flight path, and the possible interpretations of the magnetic control are reviewed in light of the known general geology.

PROGRAM FOR ESTABLISHMENT OF INTERNATIONAL SCIENCE CENTERS

In April, 1953 the directors of the Cooperative Research Foundation, California Academy of Sciences, Golden Gate Park, San Francisco, approved a program to establish and operate a number of international science centers which would serve foreign scientists and engineers visiting the major centers of scientific activity in the United States. The primary objective of the program is to stimulate direct working relationships between foreign scientists and their colleagues in the regions to be served by the centers.

Members of the SEG who reside outside the United States have been invited to avail themselves of the services offered by the International Science Center in San Francisco by telephoning BAyview 1-7314 on arrival in that city. This Center has also invited the cooperation of SEG members in the San Francisco Bay region in developing arrangements for receiving foreign scientists. In turn the Center may be able to assist local SEG members in bringing a distinguished foreign geophysicist to the area for an occasional meeting, if desired. More information may be obtained by writing to Mr.

Robert L. Champion, Cooperative Research Foundation, International Science Center, California Academy of Sciences, Golden Gate Park, San Francisco, California.

ANNOUNCEMENT
of the
NEW YORK MEETING
SOCIETY OF EXPLORATION GEOPHYSICISTS
jointly with
AAPG and SEPM

A joint meeting of the SEG, AAPG, and SEPM will be held at the Statler Hotel, New York City, on March 28–31, 1955. Authors desiring to present papers at the SEG technical sessions should submit abstracts to one of their District Representatives before December 10, 1954. Abstracts must be in the hands of the Program Chairman by December 15, 1954, to be considered for inclusion in the program. Authors will be notified shortly after December 15 whether their papers have been accepted. Members of the Program Committee for areas not covered by District Representatives will be announced in the July, 1954 issue of GEOPHYSICS and authors from such areas should submit their abstracts through such committeemen. Papers on mining geophysics should be submitted to the Chairman of the Subcommittee on Mining Geophysics, whose name will also appear in the July 1954 issue of GEOPHYSICS.

Abstracts* should be limited to not over 100 words and be submitted in triplicate in the following form and spacing arrangement:

Title
Authors and company affiliation
Abstract proper
Amount of time required for presentation
Number and size of slides or size of moving picture film
(Note: Two screens will be provided for simultaneous projection of two slides.)
Title
Authors and company affiliation } Same as above.

Prospective authors should realize that the privilege of presenting a paper before the Society entails the obligation of promptly submitting a manuscript of the paper to the Editor of GEOPHYSICS for his consideration for publication in the journal.

PERSONAL ITEMS

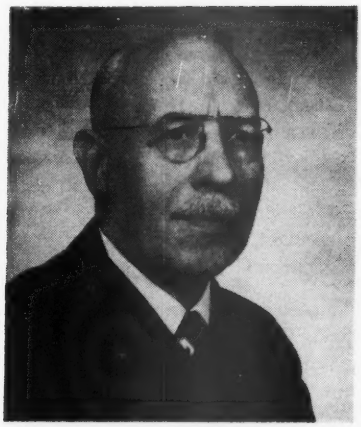
H. W. STRALEY, III, geological and geophysical engineer, is currently engaged in electrical geophysical work on iron deposits in the state of Georgia.

RODOLFO MARTIN, formerly chief geophysicist of the Y.P.F. (Argentine Government Oil Fields), has resigned his position, and joined the staff of Geophysical Service Inc. He is presently located in Salvador, Brazil, and receives his mail at Caixa Postal 324.

H. V. CROWDER, of Nance Exploration Co., is President of the Montana Geophysical Society, Billings. Other officers of the new society are J. R. WILLCOCKSON, Stanolind Oil & Gas Co., First

* See Landes, K. K., A Scrutiny of the Abstract. *Bull. A.A.P.G.*, Vol. 35, No. 7, July, 1951, p. 1660. Also in *Geophysics*, Vol. 17, No. 3, July, 1952, p. 645.

(*continued on page 382*)



E. A. ECKHARDT
Honorary Member

CONTRIBUTION FROM E. A. ECKHARDT

The Society of Exploration Geophysicists has received ten shares of common stock in the Container Corporation of America from Dr. E. A. Eckhardt, Honorary Member. On transmitting the certificate to the society Dr. Eckhardt wrote, "This contribution is made without restriction so that it may be used by the Society in any manner which its officers deem to be of benefit to its purposes."

Dr. Eckhardt was elected to Honorary Membership in 1952, and the award was presented by Dr. Sigmund Hammer, then President. Following is an excerpt from the citation.

> "Dr. Eckhardt has had a long and distinguished career in Geophysical Exploration and has pioneered its development since its inception in this country. In 1920 he gave a talk on geophysical exploration before a colloquium of geologists at the U. S. Geological Survey. This is probably the first talk on this subject delivered in the Western Hemisphere. In the following years, not excluding the present, he has been a leader in developing and promoting geophysical exploration to its present stature of world importance."

Dr. Eckhardt retired December 31, 1953 as Vice-President, Assistant Director, and Staff Geophysicist of Gulf Research and Development Company, Pittsburgh, Pennsylvania.

In his acknowledgment President Roy L. Lay said: "Those of us who have been in geophysical exploration and associated with the SEG over a period of time have been aware of your deep interest and concern both for the profession and for the society, and this gift is only further evidence of your devotion. On behalf of the Executive Committee and all of our 4,000 members, I want to thank you and wish you much happiness and good health in future years."

Vice-President; SAM MARSH, The Carter Oil Co., Second Vice-President; and JOE SIDES, Geophysical Associates, Secretary-Treasurer. Serving on the Board of Directors are R. W. GEMMER, The Carter Oil Co., and DONALD CRARY, Sohio Oil Co.

CONTINENTAL OIL COMPANY has announced the advancement of B. G. SWAN to Regional Exploration Manager in Oklahoma City, Oklahoma. His mailing address there is Box 795. Other company advances include: L. E. WHITEHEAD to Assistant Manager, Geophysical Section; FRANK SEARCY to Assistant Manager, Geophysical Division; D. S. GODSHALK, Superintendent Operations Division, Geophysical Section; H. H. MOODY, Superintendent Equipment Division, Geophysical Section; E. J. KEITH, Geophysicist, Geophysical Section; R. F. HUGHES, Assistant Superintendent, Equipment Division, Geophysical Section; C. K. JORDAN, Section Chief, Geophysical Section; and H. A. WAKEFIELD, Development Engineer, Geophysical Section.

JOE B. HUDSON has resigned his position as Acting Area Geologist in charge of Geologic Lease and Scouting for Humble Oil and Refining Company in Los Angeles to become Vice President for Operations of Monterey Oil Company, Statler Building, Los Angeles.

HENRY CORTES has been made a director of the Magnolia Petroleum Company and in addition has been assigned the position of executive in charge of Magnolia's research activities. He will continue to serve Magnolia as Assistant Manager of Land and Exploration.

ROY L. LAY, President of the SEG, has been appointed assistant to the vice-president in charge of the producing department of The Texas Company. Mr. Lay's former position as Manager of the Geophysical Department of the Texas Company in Houston has been filled by OTIS B. HOCKER. In consequence of his promotion, Mr. Lay is being transferred from Houston to New York.

LEO J. PETERS has been named a vice-president of the Gulf Research and Development Company, succeeding to the position vacated by E. A. ECKHARDT upon his recent retirement. T. J. O'DONNELL has been made Director of the Geophysical Operations Division, succeeding Dr. Peters in this position.

THOMAS R. SHUGART has been elected President of Research, Incorporated in Dallas. He was formerly a consulting geophysicist.

NAOITO KUMAGAI, Professor of Geophysics at Kyoto University in Japan, spent the six months from September, 1953 to March, 1954 in the United States. Four months of this visit was spent at Columbia University, where he made use of special computing facilities on a gravity research project. On his return trip to Japan he visited geophysical activities in Washington, Pittsburgh, Chicago, Madison, St. Louis, Tulsa, Dallas, Houston, Denver, and Los Angeles.

PROF. MAURICE EWING of Lamont Geological Observatory, Columbia University, has recovered completely from the effects of injuries suffered during his current expedition at sea when he was swept off the *Vema* near Bermuda. Of four men carried from the ship by a wave that covered the deck, three were rescued, and one, a member of the crew, was lost.

SOCIETY OF EXPLORATION GEOPHYSICISTS

Officers for 1954–55

PAUL L. LYONS, Anchor Petroleum Co., Tulsa, Okla.	PRESIDENT
ROY F. BENNETT, Sohio Petroleum Co., Houston, Tex.	VICE-PRESIDENT
HUGH M. THRALLS, Seismograph Service Corp., Tulsa, Okla.	SECRETARY-TREASURER
MILTON B. DOBRIN, Magnolia Petroleum Co., Dallas, Tex.	EDITOR
ROY L. LAY, The Texas Co., New York, N. Y.	PAST PRESIDENT

society of exploration geophysicists

MEMBERSHIP LIST

FEBRUARY 15, 1954

SOCIETY OF EXPLORATION GEOPHYSICISTS

MEMBERSHIP LIST

February 15, 1954

##Honorary	5
**Life	2
Active	2,482
*Associate	1,328
#Student	276
Total membership	4,093

CONSTITUTION

(As amended to August 26, 1948)

ARTICLE III. MEMBERSHIP

SECTION 1. The membership of this Society shall consist of persons elected and qualified in accordance with the Constitution and Bylaws of this Society at the time of such election.

SECTION 2. The membership of this Society shall consist of Honorary Members, Active Members, Associate Members, and Student Members.

SECTION 3. To be eligible to election to Honorary Membership,## a person shall, in the unanimous opinion of the Standing Committee on Honors and Awards and the Council, have made a distinguished contribution to geophysics or a related field which warrants exceptional recognition.

SECTION 4. To be eligible to election to Active Membership an applicant must have been actively engaged in practicing or teaching geophysics or a related field for not less than eight years (up to four years as a student in a recognized college or university may be counted toward this total) of which at least three years must have involved work of a responsible nature calling for independent judgment and the application of geophysical or geological principles.

SECTION 5. To be eligible to election to Associate# Membership, an applicant must be actively interested in geophysics.

SECTION 6. To be eligible to election to Student† Membership an applicant must be a graduate or undergraduate student in good standing in residence at a recognized university or college.

SECTION 7. An Honorary Member or Active Member shall enjoy all privileges of the Society. He shall be eligible to hold any office, to vote on all matters submitted to the membership, to petition the Council or Executive Committee on any matter, to sponsor applicants for membership and to publish his affiliation with the Society.

SECTION 8. An Associate Member or Student Member shall be entitled to attend the meetings of the Society, to receive its Journal and to purchase its publications, on the same terms as an Active Member. He shall have none of the other privileges of membership and in publishing his affiliation with the Society shall clearly indicate his grade of membership.

** Life membership was awarded to William W. Butler for submitting the design chosen for the Society Crest, and to O. F. Ritzmann for contribution of the Patents section of GEOPHYSICS.

A

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Jordan, W. E.
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CALIFORNIA

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Arcadia
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Lister, C. C.

Atascadero
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Tolman, F. B.

Buena Park
Holder, Homer C.

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Jakosky, J. J. Jr.
Kempsky, Phillip J.
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Kovic, Joseph D.
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Lockwood, R. Bruce
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Metzner, Loyde H.
Morris, A. E. L.
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Schultz, F. E.
Sebastian, Charles F. Jr.
Slichter, Louis B.
Sloat, John
Smith, Dick
Statham, Louis
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van der Weg, Klaas
Walling, Dean
Wallis, W. S.
Wilson, Clyde H.
Yahnke, Douglas Robert

Lynwood
Keith, Lawrence

Malibu
Sweet, Elliott

Menlo Park
Cronin, Eugene J.
Katz, Samuel

Merced
Borel, William P.
Clinton, James Morris
Hall, Robert A.

Monrovia
Tolman, F. B.

Morro Bay
Denning, Wayne H.

North Hollywood
Bertolet, Edward C.

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Swanson, Carl A.

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Drennan, William A.
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Higgins, James W.
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Johnson, Robert R.
Mosier, Wilfred C.
Tinsley, Arthur B. Jr.
Warren, David H.

Ojai
Booth, Wm. M.

Orcutt
McCullough, J. J.

Palo Alto
Miller, Stephen W.
Williston, S. H.

Palos Verdes Estates
Lockhart, Arthur A.

Pasadena
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Hartman, E. E.
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Lago, Nils
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Maureira, Artemio S.
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Spencer, Leslie C.
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Afra, Thomas S.
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Sanlav, F. M.
Spaeth, Mark G.
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Grand Junction
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Warrick, Richard Ellsworth

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Lakewood
Versaw, Francis R.

Lamar
Diamond, Paul E.

Las Animas
Klett, Richard C.

Louviers
Newmarch, George A.

Loveland
DeGood, R. G.

Rifle
Finnegan, Michael J.

Uravan
Ekren, Einar B.

Wheatridge
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Mt. Vernon
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Taylorville
Trammell, DeTroy

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Lafayette
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IOWA

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Roy, Chalmer J.

Davenport
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Des Moines
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Harlan
Christensen, Fred A.

Iowa City
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Meade
Maxey, Willard A.

Osawatomie
Chamberlin, N. J.

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Salina
Schaefer, Leo J. Jr.

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Fuqua, Henry H. Jr.
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Trombla, Lynn B.
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KENTUCKY

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LOUISIANA

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Bellican, Joseph Borie
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Raggio, Frank, Jr.

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Jeanerette
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Lowery, R. A.

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Morgan City
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Smith, Merrill
Sprague, Robert L.
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Thirkhill, Edward R
Todd, James H.
Totten, S. W.
Utterback, D D
Watson, Robert E
Wegener, R H
Williges, William A.
Winters, Rayford W.

New Roads
Enyart, Eugene A.

Opelousas
Eubank, John T
Kent, Robert Felts
Moss, Sam B.
Phillips, Jonathan W

Shreveport
Akin, Ralph H.
Appendino, John
Baker, Glenn J.
Barret, Wm. M.
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Bloomer, Philip A. Jr.
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Cooke, John Graves, Jr.
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Fazakerly, W. B.
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Ferguson, J. G.
Fischer, L. F.
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Harris, John
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Teufel, Virgil W.
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Bethesda
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MASSACHUSETTS

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Brookline
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Vozoff, Keeva

Harvard
Leet, L. Don

Lynn
Davidson, Maurice J.

North Adams
Geiser, David T.

Waltham
Hanson, Roy E.
Peoples, J. A., Jr.

Wellesley
Graham, Richard H.

Weston
Linehan, Daniel, S.J.

Woods Hole
Hersey, J. B.
Officer, Charles B.

MICHIGAN

Ann Arbor
Clements, Donald H.
Wilson, James T.

Calumet
Frantti, Gordon E.

Crystal Falls
Broman, William H.

Farmington
Chapman, Wm. B.

Grand Rapids
Kolb, John

Hartford
Erwin, John W.

Houghton
Bacon, Lloyal O.
Elliot, Charles L.
Longacre, William A.

Ishpeming
Boyum, Burton Hill

Jackson
Riedel, Robert W.

South Haven
Warner, D. F.

MINNESOTA

Minneapolis
Armstrong, Lee C.
Mooney, Harold
Willmore, Naaman W.

St. Paul
Sermon, Walter H., Jr.

MISSISSIPPI

Ackerman
Hall, John E., Jr.

Brookhaven
Barthelemy, J. E., Jr.

Calhoun City
Bourgeois, Alvin J.
O'Connor, Robert B., Jr.

Greenville
Fleming, DeWitt P.

Gulfport
Jameson, W. W.

Hattiesburg
Black, Charles W.
Brust, Richard L.

Houston
Carter, James F.
Marlin, John L., Jr.

Jackson
Allred, Willard A.
Boicourt, Stanley C.
Brown , Paul B.
Cole, Ralph C.
Crager, John A.
Duby, Bryan A.
Gaby, Ewin D.
Gaby, Phil P.
Graham, Maxwell O.
Knight, Fred G.
Myers, M. D.
Phillips, Robert R.
Pretzer, Dwayne L.
Sistrunk, John D., Jr.
Sturdevant, John M.
Voris, Richard H.

Wallner, Jack D.
Walton, William M. Jr.
Wells, Kenneth R.

Laurel
Hill, Ralph R.

Lexington
Hughes, Leslie C.

Lucedale
Koenning, Eddie Lee

Magee
Blake, Dale C.
Smith, Donald R.

Natchez
Gulmon, Gordon W.

Purvis
May, John E.

Vicksburg
Whatley, Arthur F.

Wayside
Potter, Julian F.

West Point
Ervin , James W.

Yazoo City
Harwell, Robert B.

MISSOURI

Doniphan
Grace, Lawrence E.

Fredericktown
Phebus, James E.

Jennings
Brys, Eugene C.

Joplin
Cash, Robert O.
Marsh, William T.
Miller, Bob R.

Kansas City
Leininger, Robert J.

Montgomery City
Albermissen, S. Theo.

Richmond Hts.
Riley, James T.
Riley, Louis E.
Riley, Robert C.

Rolla
Gabriel, V. G.

St. Louis
Abbott, Robert F.
Adams, William M.
Blum, V. J., S.J.
Daniels, Warren B.
Engelhardt, James R.
Fink, Don Roger
Forrest, Michael C.
Hasenpflug, Harry J. Jr.
Honnell, Pierre M.
Hummel, Anthony W.
Jacobson, Rollyn P.
Kisslinger, Robert L.
Knapp, Gregory A.
Koehler, Michael J.
Lewis, Paul K.
Macelwane, J. B., S.J.
Mara, Frank X
McCormick, John J.
Miller, Cecil C.
Mudra, Paul J.
Nuttli, Otto W.
O'Leary, Timothy D.
Opp, Albert G.
Orsini, Nicholas A.
Pantall, Jack T., Jr.
Rauschenbach, Otto
Robertson, Florence
Saunders, Barry C.
Scharon, LeRoy
Stearn, Noel H.
Webb, John P.
Whipple, Arthur Paul
Wilkat, Albert O.
Young, D. D., Jr.

Savannah
Yost, Carl E.

University City
Arata, Byron L.
Brerton, Roy
Davit, William A.
Kisslinger, Carl
McDonnell, John P.

Webster Groves
Valenta, Rudolph C.

MONTANA

Baker
Kennedy, Howard L.

Billings
Adams, Hal Robert
Allen, William G.
Barron, Charles E.
Black, Arthur W.
Brantley, L. L. Jr.
Bursk, Phillip H.
Cornell, James R.
Crary, Donald
Crowder, H. V.
Cummins, Dean L.
Davis, Charles A.
Davis, J. Lee
Dolan, John P.
Fellows, Robert A.
Fitts, Mac Elmore
Freuhling, S. W.
Gemmer, R. W.
Greenlee, Paul
Heaney, Don
Higgins, Robert Lee
Hoffman, John C.
Holloway, William L.
Hull, N. L.
Hunter, Dean T.
Iverson, W. D.
Jennings, Bruce M. Jr.
Johnson, Melvin C.
King, Thomas C.
Kirby, Gordon
Lewis, A. V., Jr.
McGee, N. W., Jr.
McGrady, Dupree
McKeever, J. H., Jr.
McMaster, Joseph T.
Menefee, James C.
Mix, A. E.
Nelson, Robert L.
Oakley, William M.
Olson, Donald L.
Parker, John M.
Paterson, Walter D.
Reeves, F. R.
Rogers, M. H.
Rouse, John T.
Schombel, Leonard F.
Shay, Daniel C.
Sides, Joe
Snodgrass, D. D.
Sonnenberg, Frank P.
Spaulding, James B.
Terry, Paul V., Jr.
Thomas, Robert P.
Whitt, Rayburn H.
Wilson, E. E.

Browning
Feeback, Lawrence D.

Chinook
Hope, Richard D.

Culbertson
Miller, Charles M

Glasgow
Peacock, H. E.

Glendive
Meadow, Harold
Rice, Paul
Rieker, William J. Jr.

Great Falls
Gribi, Edward A., Jr.

Harlem
May, John J.

Miles City
Buchner, Harry M.
Callahan, James A.
Clark, Edward C.
Clark, L. T.
Colvin, C. E.
Cox, Charles B.
Doty, J. R.
Herr, H. K.
Langstroth, Ward T.
Olson, Glen E.
Rowe, Ural A.
Smith, Hobart C.
Young, Malcolm A.

Poplar
Davis, David K.

Roundup
Parker, John C.

Scoby
Heidt, Malcolm J.
Sprinkle, D. L.
Wilson, Warren A.

Sidney
Manos, Sammy G.
Mueller, Arno P.

Wibaux
Daly, T. E.

Wolf Point
Bozman, J. R.
Hickle, W. G.

NEBRASKA

Fremont
Holm, E. Richard
Kimball
Larry, Joe P.
Orlich, Budd

Lincoln
Miller, Loren R.

Omaha
Barton, Jackson M.

Scottsbluff
Wilmot, H. G.

Sidney
Gilliland, J. R.
Gilling, Frederick S.
Mix, Leo R.
Morgan, Wesley H.
Pogue, Andrew W.
Spradlin, Samuel Theo.

NEVADA

Reno
Miller, Russell T.
Stephenson, Edgar L.

Wells,
Parkhill, J. Brooks

NEW JERSEY

Ft. Monmouth
Ostenso, Ned A.

Princeton
Bonini, William E.

NEW MEXICO

Albuquerque
Birdseye, Henry S.
Buto, George
Lohse, John M.
Long, Morris A.
Malovich, Ernest J.
Mickey, W. V.
Perret, Wm. R.
Seim, Carl Henry
Whelan, Mark
Wilson, Donald E.

Artesia
Kettle, Robert W.

Aztec
Coan, G. B.
Copeland, H. V., Jr.
McConathy, W. J.

Carlsbad
Acklin, Floyd, Jr.
Barmore, Clarence E.
Corbin, L. P.
Goddenow, Wayne Berdette
Pratt, Wallace E.
Summers, G. H.
Walker, John Richard
Wicker, M. C.
Witherspoon, D. R.

Hobbs,
Bartel, Robert R.
Jones, Robert W.
Moore, J. Hiram
Thompson, Grady

Lovington
Burton, David L.

Heinrichs, Christian C.
Hoagland, William N.
Lambright, Orbie N.
Pervinsek, Robert J.
Richey, Chester R., Jr.
Williamson, Lonnie C.

Portales
Bills, Eugene S.
Roesch, Robert C.

Roswell
Bradley, Robert K.
Cowden, Robert W.
Domenico, S. Norman
Finley, J. E.
Gilmore, Robert A., Jr.
Hughes, William R.
Livingston, E. C.
Long, C. J.
Manatov, Ilya A.
McKenzie, Chessley E.
Molinar, J. J.
Morgan, Henry W.
Perino, August J.
Scaife, W. P.
Smith, Robert V.
Willner, Carl A.

Ruidoso
Evjen, H. M.

Socorro
Gourley, Lloyd E. Jr.
Johnson, J. Burlin, Jr.
Kintzinger, Paul R.
Vacquier, Victor

Tatum
Ekstrom, James J.
Hunt, J. Richard

NEW YORK

Amawalk
Kelly, Sherwin F.

Brooklyn
April, Howard L.

Corning
Hammond, Dean H.

East Syracuse
Nash, Cleve C., Jr.

Larchmont
Lundy, Barry R., Jr.

Little Neck
Collins, William O.

New York
Brant, A. A.
Brilliant, R. M.
Caan, A. J. Z.
Cash, Harvey, Jr.
Donna, John M.
Drake, Don F.
Flittie, Clifford G.
Fryer, Theo. B. Jr.
Hardy, W. W.
Hazen, George H.
Kaufmann, G. F.
Kogbetliantz, Ervand
Lynch, J. J., S.J.
Olson, W. S.
Racek, Edward W.
Sauve, N. B.
Scott, Robert F.
Shaffer, Richard E.
Slotnick, M. M.
Tucker, Lewis R.
Vajk, Raoul
Van der Sleen, N.
Voegeli, Richard A.
Voukovitch, Boris
Whiton, H. F.

Nyack
Tolstoy, Ivan

Palisades
Drake, Charles L.
Ewing, Maurice
Jennemann, Vincent F.
Miller, Edward T.
Press, Frank
Worzel, John

Syracuse
Kopka, William

Troy
Beers, Roland F.
Klaasse, J. M.

Wellsville
Young, Wilbur H. Jr.

NORTH CAROLINA

Hendersonville
Taney, Norman E.

Monroe
Houston, Robert S.

NORTH DAKOTA

Beach
Ames, Richard F.
Riendl, Joseph A.

Belfield
Oram, Peter M.

Bismarck
Armstrong, Orven H.
Ashby, Julian C.
Banchio, Francis J.
England, C. M.
Jenson, James J.
Lechtenberg, W. F., Jr.
Peterson, F. A.
Pratt, Ernest
Smith, Oscar Edwin, Jr.
Vanderbeek, James W.
Willis, Howard A.
Zieve, Robert L.

Bottineau
Nichols, Thomas C., Jr.
Peffer, John C.

Bowman
Chance, Jenner K.
Davis, Robert M.

Dickinson
Geyer, Robert L.
Hart, Corby L.
Hayes, Quin
Hazelrigg, J. B.
Mitchell, Gerald E.
Nix, Roy Leonard

Mott
Black, Robert J.
Johnston, Jerry

Parshall
Strozier, Orville A. Jr.

Watford City
Black, Robert J.

Williston
Brensing, Vernon Lee
House, J. P.
Hughes, James R.
Kaehn, Charles H.
Miller, Lloyd C.
Reinhardt, Alvin C.

OHIO

Cleveland
Berggren, Charles F.
Birkenhauer, Henry F. S.J.
Ellison, Bob Earl
Kostra, Walter
Walter, E. J.

Columbus
Heiskanen, W. A.
Pincus, Howard J.

Dayton
Koenig, Palmer E.

Findlay
Konkel, P. M.

Springfield
Wojciechowski, W. A.

Willoughby
Willis, David E.

OKLAHOMA

Anadarko
Evans, Hugh, Jr.

Antlers
Olson, Odell C.

Ardmore
Carmack, Roy P.
Pierson, Jack N.

Bartlesville
Allen, William E.
Beck, Ronald E.
Bondurant, J. E.
Bradley, R. M.
Brownlow, Cecil L.
Courtier, Wm. H.
Crenshaw, C. C.
Elliott, S. D.
Ericson, Harry B.
Hintze, A. J.
Johnson, E. W.
McNally, Perry M.
Mendenhall, H. L.
Miller, Vincent
Morriss, Floyd H.
Piety, R. G.
Rice, R. B.

Broken Arrow
Hawkins, J. E.

Clinton
Eastes, William T.
Ellis, Clifton A.

Dewey
Johnson, J. R.

Duncan
Neece, Neal, Jr.

Durant
O'Halloran, Daniel J.

Edmond
Jones, Leland W.

Elk City
Seamans, F. Augustus

Enid
Braithwaite, Al
Caldwell, Walter T.
Clifton, R. L.
Fry, William C.
Hillery, R. R.
Naugle, Charles E.
Newell, James Willard
Nicholls, Harry R.

Ft. Gibson
Graves, John Milton

Henryetta
Carter, Norman A.

Lawton
Moran, J. R.

McAlester
Gagnon, Stewart P.

Norman
Gaither, Jerrel W.
Johnson, Hamilton M.
McGuckin, Glenn M.
Norden, John A.
Redish, William L.
Schriever, William
Tolgay, Mitat Y.

Oklahoma City
Abbott, Wayne R.
Anderson, Geo. E. Jr.
Arkle, John P. Jr.
Beebe, B. W.
Bemrose, John
Bleyberg, Arnold H.
Cash, Robert Lee
Cody, C. C.
Cunnyngham, Earl F.
Davis, Richard M.
Deupree, Edwin A.
Dunn, George V.
Dunwoody, Robert H.
Ervin, L. D.
Fee, S. T.
Foster, John R.
Hadler, Harry G.
Hawes, Julian
LeBay, William D.
Miller, R. D.
Morrisey, Norman S.
Mount, E. L.
Murphy, Boyd F.
Peacock, Robert H.
Pinney, Earl T.
Ratliff, D. W.
Roane, W. H.
Roberts, F. A.
Roberts, R. D.
Standridge, James A.

Stones, J. Eugene
Swan, B. G.
Sykes, Howard A.
Talley, H. C., Jr.
Wagner, W. C.
Warren, P. R.
Wolff, D. J.
Wood, Carroll A.

Okmulgee
Busby, Julian M.

Pauls Valley
Browder, Walter C.
Bynum, George R.
Foster, G. A.

Pawhuska
Barber, R. Curtis

Ponca City
Barnes, Richard P.
Becker, Adrian A.
Bird, Wesley E. Jr.
Bloodworth, Dennis A. Jr.
Caro, William B.
Cobb, Arthur Tom
Crawford, John M.
Davis, Warren L.
Dehlinger, Peter
De Witte, L.
Dinstel, Woodrow L.
Doty, William E. N.
Fickinger, E. E.
Fowlkes, Charles W.
Gaebe, James R.
Gaither, V. U.
Garten, Roy, Jr.
Godshalk, D. S.
Goupillaud, Pierre L.
Haggard, Wiley R., Jr.
Jordan, C. K.
Kieth, Edwin J.
King, Laurence K.
Laing, William E.
McGlone, Joseph F. Jr.
Mitchell, Donald E.
Moody, Herbert H.
Moxley, Stephen D., Jr.
Pelton, Charles R.
Searcy, Frank
Sigle, Gene
Smith, Ben Ward
Turner, Lewis K.
Vorheis, Byron
Wells, E. L.
Whitehead, Loren E.
Witcher, Leland G.

Pond Creek
Johnson, William H.
Mogg, George G.

Prague
Klabzuba, Robert E.

Proctor
Young, Dewey D.

Sayre
Brock, Charles D.
Collins, Warren

Shawnee
Gibson, G. D.
Henderson, Bill
Lukens, John P.
Schaeffer, Hugh C.
Smith, Delbert F.

Stillwater
Hurt, Walter L.

Tulsa
Abel, Karl W.
Alexander, Warren A.
Andrews, H. H.
Arnold, Tapley G.
Austin, Arthur Cecil
Ballou, Albert L. Jr.
Barthelmes, Albert J.
Baswell, W. P. Jr.
Bayer, Kenneth C.
Bayhi, Joseph F.
Bediz, Pertev I.
Bennett, Owen B.
Benson, A. E.
Bentley-Llewellyn, J.
Bernard, Leonard
Bevan, Thomas J.
Bevington, Devon J.
Bills, Robert N.
Bishop, F. L.
Bisol, D. L.
Blackledge, Glenn E.
Blakey, Carl W.
Boucher, F. G.
Bonnette, Ibrey T.
Borman, Frank W.
Born, Wm. T.
Bowie, Duncan M.
Bowman, D. C.
Breck, Howard R.
Brinnon, W. B.
Broadbent, B. R.
Broding, Robert A.
Brown, Frank E.
Brown, Henry W.
Brown, Warren A. Jr.
Bryan, A. B.
Buckie, LeRoy S. Jr.
Buelow, James W.
Buffum, C. Emery
Burk, John William
Cady, Francis H.
Campbell, Edmund O.
Campbell, Francis F.
Catt, James L.
Clark, R. C.
Clayton, Neal
Clements, W. E. R.
Clote, Thomas A.
Cochrane, David W.
Coffin, R. Clare
Collier, John J.
Connell, Joe E.
Cooley, Elihu H.
Cooper, Harvey F.
Cooper, Jack R.
Coryn, F. R.
Coster, H. P.
Cressman, K. S.
Cronin, Stewart
Crossland, Edward J.
Crump, W. W.
Crumrine, Kenneth C.
Cunningham, Wm. J.
Damon, Everett F.
Davis, D. R.
Davis, John C.
Day, Chas. E.
Dimmick, Opie
Dix, Max W.
Duller, Charles E.
Durant, C. P.
Dyk, Karl
Dzwons, George S.
Edmonson, Carl L.
Egan, Daniel G.
Eisler, Joseph D.
Ellsworth, E. W.
Engle, A. Wendell
Erdahl, William M.
Eshelman, Harry S.
Etnyre, John B.
Evans, Julian F.
Farrell, Joseph P.
Faust, Lawrence Y.
Fearon, Robert E.
Ferguson, John L.
Ferguson, Joseph W. Jr.
Ferris, Craig
Filson, H. F.
Finley, R. K.
Finn, Robert S.
Franklin, John V.
Freymuth, J. J., Jr.
Friendly, Jack L.
Frossard, R. L.
Garner, J. P.
Garrette, F. I.
Garrity, T. A., Jr.
Gilliam, J. T.
Gilmore, Robert J.
Gilmour, Andrew
Giulio, Stanley E.
Godell, John J.
Goetz, Louis P.
Green, Robert P.
Green, T. S.
Hadley, Charles F.
Hammond, J. W.
Handley, E. J.
Handley, Ed. M.
Harbach, Robert G.
Harlow, Robert O.
Harlton, Bruce H.
Hart, Walter S.
Hartline, Ralph E.
Hawpe, Franz M.
Heap, W. O.
Heidt, Arnold, Jr.
Heineck, Robert L.
Hess, Frank R., Jr.
Hickey, J. T.
Hidy, John H.
Hilliker, Robert D.
Hobart, Henry M. Jr.
Hockaday, H. Ray
Holland, Richard R.
Houchins, Guy M. Jr.
House, A. Maxwell
Hurry, Clare N.
Hutchinson, John S.
Hyatt, Charles W.
Ingalls, Philip C.
Ingle, Gerald W.
Innes, Arland I.
Jackson, C. Kenneth
Jackson, Judson G.
Jameson, Chet H., Jr.
Jett, Glendon D.
Johnson, James F.
Jolly, R. N.
Jones, Joe H.
Jones, Stuart A.
Jones, V. L.
Kartman, Douglas J.
Kaschak, George R.
Kastner, Oscar J. Jr.
Kelley, William E.
Kendall, Robert C.
Keselik, Joseph
Keys, Robert T. Jr.
Kezeler, J. L.
Kiess, Myron C.
Kitchen, James H.
Kittredge, F. R.
Knowles, J. G.
Kochendorfer, A. J.
Koeppel, B. W.
Kosarek, John H.
Lahmeyer, John D.
Lamb, William C.
Lambe, John P.
Lamkin, Woodrow W.
Lang, Harold M.
Lash, Charles C.
Lawrence, Franklin L.
Lawrence, H. W.
Lawrence, K. M.
Lawrence, Wm. P.
Laws, J. O.
Leas, Ruth R.
Lee, Richard E.
Leedy, F. B.
Lima, Ibsen C.
Locke, Edgar R.
Lynn, Ralph D.
Lyons, Paul L.
Major, Maurice W.
Manhart, T. A.
Martin, Dick
Martner, Samuel T.
Marucheck, Joseph L.
Massis, Cliff H.
Mathieson, Raymond L.
Maxey, J. R.
Mayes, Tom D.
McAlister, C. H.
McAnally, Donald E.
McClure, C. E.
McCollum, E. V.
McCormick, Max D.
McCracken, Guy I.
McKenzie, D. B., Jr.
McManis, Louis B.
McMillen, Ralph E.
McMunn, Charles E. Jr.
McNatt, E. M.
Miller, James W.
Mills, Robert G.
Mitchell, Fielding L.
Moore, Homer C.
Moore, Robert L.
Morris, Lauren G.
Mossman, R. W.
Moynihan, C. S.
New, James R.
Newton, George R.
Novelly, Walter O.
Oksa, Donald R.
Oliphant, Charles W.
Owen, H. E.
Palmer, John E.
Parmenter, H. R.
Patterson, L. J.
Pelzer, H. L.
Pennington, Wallace E.
Pentecost, Claud D.
Perkins, William R.
Peterson, Glen
Peterson, V. A.
Pick, Albert L.
Pirson, Sylvain
Pittman, Robert R.
Pohly, Richard A.
Pottorf, Newell
Preston, B. G.
Pugh, Wm. E.
Putnam, Melvin E.
Quigley, M. Darwin
Rankin, C. T.
Reed, David E.
Reed, George W.
Rees, Wesley W.

Reid, A. C.
Richardson, H. L.
Ricker, Norman
Ries, John A.
Riggs, R. J.
Roberts, James Everett
Roberts, P. E.
Robertson, K. A.
Robinson, W. B.
Robinson, William J.
Roe, Edward Owen
Roemer, C. D.
Rollins, J. C.
Rosenbach, Otto
Ross, C. M.
Ross, Richard R., Jr.
Rummerfield, Ben F.
Rupnik, John J.
Rutledge, Richard B.
Salisbury, Thomas R.
Saubert, R. W.
Schedler, George D.
Schempf, Edw. G.
Scherbatskoy, S. A.
Schmalz, Herman J.
Schoellhorn, S. Wm.
Schubert, Raymond D.
Scott, C. B.
Shannon, Charles A., Jr.
Shannon, Charles W.
Sheehy, Marshall
Shivers, Grover C., Jr.
Sibley, W. B.
Silverman, Daniel
Sims, Robert L.
Smith, Cyril B.
Smith, Edwin F., Jr.
Smith, G. N.
Smith, W. N. M.
Snow, Leland
Sorge, William A.
Southgate, Tom F.
Sparks, N. R.
Sprinkle, Don L.
Stafford, John A.
Steed, Paul H.
Stover, Edward B. Jr.
Strachan, Clyde G.
Swanson, Donald C.
Swearingen, A. C.
Sype, William R.
Taylor, Albert
Taylor, Garvin L.
Tedder, Joseph W. Jr.
Thayer, J. M.
Thomas, Lloyd O.
Thomas, Thomas J.
Thompson, R. R.
Thomsen, Erik, Jr.
Thomsen, Harry L.
Thralls, H. M.
Van Cleve, R. F.
Van Horn, William H.
Van Orden, Keene C.
Vernon, Jess
Von Croy, Stefan
Waddell, V. H.
Waldrep, W. Day
Wallace, B. W.
Walton, George G.
Warren, Howard B.
Weatherburn, K. R.
Weatherby, B. B.
Weichert, David R.
Weingartner, R. A.
Weltsch, E. H.
Westby, G. H.
Westphal, J. A.
Weyer, John F.
Whitaker, Rayford L.
Widess, M. B.
Wiechert, Rudolph F.
Wilcox, Stanley W.
Williams, P. S.
Williams, Richard
Wilson, James N.
Winn, Clayton N.
Woodburn, James E.

Watonga
Strozier, Robert J.

OREGON

Aurora
Lester, O. C., Jr.

Grants Pass
Goldenstein, S. J.

Mt. Vernon
Culp, Harold A.

PENNSYLVANIA

Bethlehem
Angino, Ernest
Bond, James P.
Gallagher, Robert T.
Harmon, Richard C.
James, Robert W.
Smith, James G.

Bradford
Scholl, E. S.

Chadds Ford
Sharp, C. Sheldon

Ebensburg
Bender, Fred A.

Emmaus
Miller, Jesse A.

Gibsonia
Fink, Paul O.

Madera
Capatch, Victor F.

Mechanicsburg
Dickson, James A.

Newton Square
Johnson, F. L.
Mayes, Fred M.

Norwood
Bazzoni, Charles B.

Oakmont
Muffly, Gary
Sims, Jess O.
Smith, Douglas H.
Whitley, Joseph M. Jr.

Palmerton
McMurray, Howard V.

Philadelphia
Agocs, W. B.
Jensen, Homer

Philipsburg
Mandel, Peter, Jr.

Pittsburgh
Affleck, James
Alexander, Frank C. Jr.
Allen, Frank T.
Allon, Michael
Aszklar, Stanley J.
Baade, John H.
Backman, John E.
Bailey, Lothrop H.
Bardeen, Thomas
Barton, Edward I.
Baudoin, F. F.
Boardman, Dorothy M.
Burkemper, Robert R.
Butler, Mark D.
Carter, R. B.
Clement, Paul F.
Copeland, Douglas S.
Coughlin, Edward G.
Dean, William C.
Demshar, Ludwig S.
Durbin, Howard A.
Earl, John H.
Eckhardt, E. A.
Elkins, Thomas A.
Farr, Edwin H.
Frankenberger, Zdenko
French, John R.
Galpin, Sidney S.
Gardner, Louis W.
Gealy, Wendell B.
Hammer, Sigmund I.
Hastings, W. K.
Head, E. I.
Heck, Henry W.
Heggblom, J. Roger
Herron, Robert C.
Howe, Paul E.
Hugus, John A.
Krivoy, Harold L.
Livo, George O.
Lugenbill, John M.
McKee, Alexander H.
Melchior, Louis F.
Meszaros, W. A.
Murphy, William H.
Newman, Conrad E.
O'Donnell, T. J.
Palmer, E. M.
Palmer, Loyal D.
Pappas, Constantine N.
Penry, William T. III
Peters, L. J.
Peterson, Wendell E.
Reiser, Robert S.
Ritzmann, O. F.
Robinson, John L., Jr.
Ross, Ralph B.
Sander, George W.
Scott, J. Lewis
Southwick, Peter F.
Swanson, E. Keith
Texter, John W.
Thomas, Howard E.
Turcotte, F. Thomas
van Nostrand, D. J.
Wardell, John M. Jr.
Watson, George R.
Weber, David M.
Wickerham, W. E.
Wigbels, Frank B.
Wyckoff, R. D.
Zacher, Irving C.

Portage
Cervik, Joseph

State College
Andrews, Alday B.
Berg, Joseph W. Jr.
Chapman, Robert
Duecker, John C.
Holmes, Charles R.
Howell, B. F., Jr.
Keenan, Curtis H.
Lopez-Liwares, Manuel
Scheffey, Paul L.
Smith, Donald A.
Stengal, Eugene

West Pittston
Gill, Robert C.

RHODE ISLAND

Jamestown
Prade, Nat H.

Providence
Henkel, John H.

SOUTH CAROLINA

Johns Island
Rivers, J. C. S.

Belle Fourche
Minton, Richard B.

SOUTH DAKOTA

Faith
Smith, Melvin M.

Mobridge
Grosse, Will Alex

Rapid City
Becker, Clarence W.
Ludwick, C. C.
Newmarch, George A.
Young, T. Eugene

Weaver
Rudolph, William E., Jr.

TENNESSEE

Knoxville
Colman, Hugh C.

Oak Ridge
Banta, H. E.
Garrett, Geo. A.

TEXAS

Abilene
Arnold, Maurice E.
Crider, Lewis C.
Davis, Wm. W.
Grange, Donald C.
Tefft, Gerald H.

Alpine
Bevier, George M.

Alvin
Hunt, Billy Dean
Moore, James M

Amelia
Hastings, E. S.

Amarillo
Kern, Jack C., Jr.
Pool, Robert C., Jr.

Andrews
Heydon, D. F.

Aransas Pass
Newton, Robert A.

Arlington
Mayfield, Cecil W.

Austin
Adamson, W. H. Jr.
Babock, Walter R.
Cartwright, Jack C.
Horton, C. W.
Hughes, Darrell S.
Lewis, Walter S., Jr.
Reed, Charles B.
Rucker, James H.
Stenson, Harry R., Jr.
Thomas, Earl
White, Gifford E.
Woodward, Thomas C.

Bay City
Eckley, Wesley

Beaumont
Bills, Samuel E.
Blanchette, A. J.
Christian, Fred H., Jr.
Ellis, L. G.
Evans, William T.
Feist, Wiley R.
Gammon, Orin Rex
Greener, Charles E.
Hagemann, R. F.
Henson, Robert L.
Herman, Alvin
Hollingsworth, W. E.
Hopkins, Richard
Jantz, O. I.
Koenig, Robert J.
Konz, Leo W.
Lavergne, Arthur J. Jr.
McCalpin, George A., Jr.
McCormack, Harold R.
McIntosh, W. D.
McKeever, Carl D.
Miller, Thomas F.
Millington, John W.
Noble, Francis H.
Parker, Herbert
Patrick, William R.
Pierce, Russell, Jr.
Stokely, Paul W.
Tiller, Wesley A. Jr.
Vreugde, T. L. J.
Waddell, William R.
Weston, Horatio C.
Winterhalter, A.

Beeville
Claunch, Elton B.
Jackson, R. S.

Bellaire
Butler, Roy
Cowles, Laurence G.
Donnerstag, Philip
Guyod, Hubert
Herzog, Gerhard
Hibbler, A. J.
Hubby, L. M.
Huffman, Charles H.
Itria, Oswald
Lee, B. D.
Manes, O. B.
Mann, Ralph W.
Mather, W. Scott
McElree, George D., Jr.
McCravey, LeRoy
Norman, Clarence D.
Nottlin, William O.
Ott, Lawrence N.
Redding, Vernon L.
Smith, Roy O.
Templeton, James H.
Thompson, Andrew A.
Treybig, J. A.
Van Siclen, D. C.
Wahl, Carl C.
Watzlavick, Joseph D.
Wendenburg, Otto

Big Lake
Allan, Sam W.
McKinley, James C.
McReynolds, P. T.
Richardson, William E.

Big Spring
Barnes, Chester F.
Butts, James Y.
Dahse, Clem A.
Davis, David A.
Gullick, Carl H.
Penn, Edgar R.
Sakovics, Julius
Stouse, Robert G.

Bonham
Davenport, Robert

Brenham
Cross, James H.

Bridgeport,
Tweddell, Ralph D.

Brownfield
Bohanon, Wayne F.

Brownwood
Salyer, James L.

Bryan
Blank, H. Richard, Jr.
Clark, Francis A. Sr.
Hayes, Donald B.

Campbell
St. Clair, Virgil

Canadian
Carter, James F.
Clark, K. M., Jr.

Cisco
Porter, C. P.

Cleyburne
Michael, Thomas G.

Coleman
Franklin, Louis

College Station
Frazier, M. L
Fritz, Joseph F.
Fuller, Eugene T.
Goedicke, T. R.
McMurry, Melville B.
Sheffield, Donald H.

Columbus
Etheridge, K. E.

Corpus Christi
Baird, John M.
Baker, Charles M.
Bolinger, J. W.
Bursk, Phillip H.
Coffin, Miller G.
Daugherty, C. G., Jr.
Durham, Charles A.
Elms, Benjamin M.
Hessi, William R., Jr.
Hoover, Lawrence E.
Hubner, B. G.
Jewell, David F., Jr.
Mason, C. C.
McCubbin, Roy H.
McDaniel, C. M., Jr.
Nelson, James K.
Teasley, Samuel A.
Thompson, Norman E.
Whaley, William J., Jr.
Wood, A. B.

Corsicana
Thompson, Wilbur L. Jr.
Throop, William H.

Crockett
Hope, May J.

Crosbyton
Faubion, Charles G.
Persinger, Richard R.

Crowell
Zwiebel, George H., Jr.

Crystal City
Mitchell, Jesse A.

Cuero
Wisda, John

Dalhart
Chalker, Bruce O.
Gullickson, W. D.
Plumb, Paul S.

Dallas
Acrey, Donald O.
Agnich, Fred J.
Alcock, E. D.
Aldrich, Richard W.
Amis, W. H., Jr.
Anderson, Russell
Andrews, Reagan H.
Arnett, R. D.
Arnett, Richard A.
Arnold, Kingsland
Ayres, J. Otis
Banks, James O. Jr.
Banning, John A.
Bays, David Scott
Bazhaw, W. O.
Blattner, Sanford D.
Bogart, Bobbie Joe
Bonebrake, Walter C.
Boone, James H., Jr.
Bradley, William
Breedlove, Ruth
Brock, Fred A.
Brooks, Robert R.
Brouillette, Etienne
Brown, H. Hallock
Brown, Jackson W.
Burg, K. E.
Burkman, Bill C.
Burrows, Hiram W., Jr.
Bussard, William H.
Busteed, W. J.
Byers, Richard E.
Capp, J. T.
Carpenter, Michael C.
Carrow, James O.
Chamberlin, C. W.
Chappell, James W.
Chase, Marvin C.
Clewell, Dayton H.
Clifford, O. C., Jr.
Cline, Paul J.
Cloepfil, Gordon D.
Cobb, Howard L.
Coleman, Robert V., Jr.
Collingwood, D. M.
Collins, Francis, Jr.
Collom, Alfred J.
Conant, E. E.
Condren, Patton
Congdon, R. L.
Conklin, Glenn M.
Conroy, Richard L.
Cooper, Jesse F.
Cornelison, Boyd
Cortes, H. C.
Coursey, W. Dudley
Cundiff, Jerry Allen
Dahm, Cornelius G.
Davidson, David B.
Deford, H. L.
DeGolyer, E. L.
DeLoach, Edward L.
Denn, William J.
Denton, D. M., Jr.
Dixon, H. B.
Dobrin, Milton B.
Dobyns, D. R.
Donnally, Chester J.
Doss, Carson L.
Douglas, Norvel
Duchscherer, Wm. Jr.
Dugan, Albert F.
Dunagan, Lillard C.
Dundon, Robert
Dunlap, H. F.
Dunlap, R. C., Jr.
Edmonston, William J.
Eley, James C.
Elliott, Clinton H.
Ellsworth, T. P.
Evans, Bobby L.
Evans, Sam L.
Everett, R. D.
Fagg, David Bruce
Farrow, B. D.
Fauser, Walter B., Jr.
Faust, Elmer J.
Fisher, Guy W.
Fisk, Frank K.
Fjelstul, C. R.
Floyd, Roy
Foote, Lewis C.
Fowler, Frederick B.
Frick, Herbert C.
Frost, H. H.

Fuller, John Frank
Fuller, Roy Lee
Garrett, M. M.
Gartwaite, Ivan H.
Gary, James W.
Gautreaux, Jos. H.
Geer, J. T.
German, Mathias George
Giles, Benjamin F.
Gill, John D.
Gillin, John A.
Glover, George D.
Godbey, John K.
Graebner, Robert J.
Graham, Leroy G.
Granberry, H. E.
Green, Cecil H.
Green, John W.
Gregg, Ward R.
Griesedieck, B. H. Jr.
Griffin, W. Raymond
Gsell, R. N.
Guipre, Robert W.
Haggerty, P. E.
Hall, Levi H.
Hamm, W. D.
Hanna, Ian B.
Harkey, W. J.
Harkness, T. O.
Harmon, B. F., Jr.
Harris, S. T.
Hartley, T. R.
Haseltine, Harvey M., Jr.
Hathaway, Milton S.
Haynes, C. G.
Henderson, J. B. H.
Hern, John Louis
Heroy, W. B.
Heroy, Wm. B. Jr.
Hicks, Warren G.
Hieatt, Herbert F.
Hightower, C. H.
Hillman, W. Jr.
Hogg, William B.
Hollis, Jack L.
Holmes, G. T.
Holmes, Odie M.
Horn, J. W.
Howard, Geo. A.
Hughes, V. C.
Hunt, Hubert B.
Imle, John F.
Isensee, George W.
Jasinski, E. J.
Johnson, Curtis H.
Johnson, Lloyd
Jones, George R.
Jones, Hal J.
Jonsson, J. E.
Jopling, D. W.
Karcher, J. C.
Kelly, James D.
Kelsey, Martin C.
Kennedy, Edward P.
Kennedy, Frank H., Jr.
Kiely, Charles M., Jr.
Kiesler, Ernest A.
Kittens, Marvin C.
Kitzman, A. C., Jr.
Knott, Robert J.
Kovelan, Edward C.
Kraye, Robert F.
Lamm, Robert J.
Lamont, William A.
Lawrence, Philip L.
Lee, Ingram, II
Lester, John A.
Levanthal, Stanley M.
Linehan, A. L.
Lipscomb, Earl W.
Lipson, Leonard B.
Livermore, Howard W., Jr.
Livingston, H. Raymond
Lodge, James T.
Logue, L. L.
Lohrentz, Don
Lontos, Jimmy Tom
Loper, George B.
Loyd, Edward R., Jr.
Luker, Robert W.
MacNaughton, Lewis W.
Mann, Neil W.
Manning, Bob N.
Marshall, Harold D.
Mayhew, Charles M
McBurnett, Harry, Jr.
McBurney, C. G.
McConnell, E. B., Jr.
McCain, Hugh, Jr.
McCarver, Holland C.
McCoy, G. W.
McDonal, Frank J.
McDermott, Eugene
McGehee, T. S.
McGiboney, James C.
McManus, Jack V.
McMullin, E. F.
Miller, Jeff E.
Mitchell, Geo. D. Jr.
Mitchell, W. R.
Moore, F. A.
Morgan, Chas. Gill
Morrison, Blackstone L.
Murphy, John T., Jr.
Musgrave, Albert W.
Mut, Stuart C.
Myers, John R.
Nash, David M., Jr.
Nash, Paul E.
Neitzel, Edwin B.
Nelson, Jerome S.
Noble, Graves E.
Nogami, Henry H.
Olson, Robert W.
Page, John S.
Parker, John Chapman
Paslay, L. C.
Pattersen, Robert W.
Patton, C. E.
Peacock, Elwin M.
Peacock, H. B.
Pennington, Dearyl E.
Pennington, Jerry B.
Pernell, J. H.
Perryman, J. D.
Peterson, J. S.
Pettersen, Robert W.
Pfleuger, John C.
Pittman, C. V. A.
Price, J. V.
Price, Lee H.
Prickett, Tom, Jr.
Pritchett, Wm. C.
Radebaugh, Robert P.
Ralph, Pierson M.
Randel, George A.
Ransom. J. H.
Reagor, Edward C.
Reeves, James N.
Renner, Darwin S.
Rettger, Robert E.
Richards, David C.
Rielly, John F.
Riggs, Emmet D.
Roberson, Charles Boone
Rollins, J. Frank
Roper, W. B.
Ruback, Norman
Russell, Dallas L.
Rutherford, Charles R.
Sanford, Robert E.
Scheel, David R.
Scott, William B.
Seiler, Geo. E.
Sell, Wayne E.
Sengbush, Raymond L.
Shook, Earley M.
Shugart, T. R.
Shuler, Ellis W., Jr.
Simen, Randolph F.
Sledge, Thomas C.
Smith, A. Horton, Jr.
Smith, Bryan F.
Smith, Charles W.
Smith, Harold D.
Smith, Randolph
Snyder, Richard
Sole, Lewis H.
Sorrels, B. J.
Spencer, James F.
Spiers, James C.
Stanfield, J. W.
Stephens, Ernest, Jr.
Stephens, J. L.
Stewart, Alexander T.
Stoutjesdyk, P. S.
Stripling, Allen A.
Stuart, Carlton E.
Stulken, E. J.
Swift, Gerald G.
Tait, Jess Thomas
Thornton, Joseph W.
Toomey, Eugene J.
Totzke, Frank D.
Towles, Henry C. Jr.
Trask, Hugh A.
Tripp, R. M.
Tronrud, Roy W.
Troseth, Frank P.
Trostle, T. D.
Tubbs, Kenneth Ray
Turner, Gerald L.
Underwood, Wayne L.
Utesch, John C.
Valkus, James W.
Van Nostrand, Robert
Venker, Donald P.
Vetter, Edward
Walker, G. B.
Wallis, Thomas F., Jr.
Walsh, T. N.
Walters, C. G.
Walton, Paul L.
Warrick, Thomas R.
Waters, Kenneth H.
Wayland, John R.
Weatherby, S. Preston
Weaver, Irvin P., Jr.
Weisbrich, R. A.
Werth, Henry C.
White, Gale
White, J. E.
Whorton, L. P.
Williams, Charles C.
Williams, Floyd J.
Williams, Ocie G.
Williams, Ralph K.
Willis, Ben E.
Winn, C. L.
Wise, Henry F.
Wissemann, Hilmer J.
Wodrich, Frank W.
Wood, Erman A., Jr.
Woolley, William C.
Wright, John W.
Yost, W. Jacque
Zivney, James R., Jr.

Del Rio
Davidson, G. B.

Dell City
Lynch, Jack

Desdemona
Friday, Marion T.

Duncanville
Berry, James E.

Eastland
Wellman, H. D.

Edna
Blair, John F.

El Campo
Hays, Clyde L.
Sanders, George W.

Eldorado
Edmiston, Billie P.
Lee, Claude S., Jr.

Ferris
Winn, Billy

Ft. Stockton
Anderson, Richard C.
Barnum, Warren R.
Dick, Charles W.
Douglas, Jas. Y.
McConnell, Robert

Ft. Worth
Anderson, Owen Wm.
Anderson, Vernon K.
Baile, R. A.
Baird, Walter D.
Balbin, Paul D.
Beard, John G.
Bell, George A., Jr.
Belt, George R.
Blatt, Henry E.
Bledsoe, M. O.
Boring, Burl J.
Botkin, John N.
Bradley, Waring
Buller, Leonard K.
Childress, Kay H., Jr.
Clendening, C. C., Jr.
Cole, E. G.
Dana, R. H.
Dayton, Morris E. Jr.
Deaver, William W.
Deegan, Charles J.
Divelbiss, James
Dudley, Raymond W.
French, John R.
Gemmill, E. J.
Greenfield, Clifton O.
Harmonson, John R.
Harrell, J. G.
Harris, Sidon
Harvey, Castle J. C.
Hassenfratz, Charles A. Jr.
Hollingsworth, W. W.
Itten, Howard

Jones, Charles R.
Kerbow, R. B.
Kerr, V. Robert
Krieg, Edward A., Jr.
LaNeve, R. O.
Lang, Ralph H.
Ledyard, Paul H.
Lee, Lynn K.
Lockett, Gwendolyn P.
Lomax, C. J.
Lombardi, Leonard V.
Lovejoy, J. B.
Matthews, E. W., Jr.
Mayo, H. B.
McCleary, H. G.
McClung, Alton
McCreary, Dosh T.
McDavid, P. M.
McGee, William G.
McKay, A. E.
McLemore, Ethel Ward
Mitchell, Bascom L.
Morris, James L.
Mortlock, F. O.
Neff, W. D.
Normand, Spencer R.
Parker, Everett H., Jr.
Prokesh, H. E.
Robinson, B. B. Jr.
Rowe, A. J., Jr.
Rutherford, Robbie
Sanders, C. W.
Scoggin, Hollis A.
Seal, W. A., Jr.
Seaman, L. O.
Schouten, F. H.
Simmons, Cal Yates
Smith, Wendell R.
Stanford, John F., Jr.
Strange, O. A.
Suggs, Millard L.
Thompson, Howard F.
Turman, Thomas R.
Van Steenbergh, S. K.
Ward, Charles J.
Warren, Kirby J.
Webster, John Marshal
Wert, Carl M.
Wilson, John H.
Wilson, John H. III
Woods, Delmer M.

Galveston
Becker, Robert C.
Gilleland, Kenneth R.
Goodfellow, Robert T.
Kale, Henry W.
Parrish, Jerry James
Ramey, B. J.
Wentaer, Bruce C.

Garland
Baker, Buford M.
Green, W. G.
Oden, A. J.
White, R. H.

Gatesville
Foote, Richard Q.

George West
Rowley, C. R.

Georgetown
Rader, William P.

Giddings
Archer, Milton

Gonzales
Schurig, Fred Max

Grapevine
Deacon, L. E.

Hallettsville
Gilbert, G. G.

Hamilton
Stiles, Miss E.

Hearne
Wolf, Mike

Hebbronville
Fritts, G. E.

Hereford
Dees, James Alec., Jr.
Herr, Wilfred C.

Hillsboro
Rath, Otto C.

Hondo
Dannemiller, George D.

Houston
Abbott, William C.
Adams, Weaver W.
Aden, James Douglas
Adler, Joseph L.
Akkerman, R. P.
Allen, Stanley R.
Amery, George B.
Anderson, John F.
Andrews, Robert T., Jr.
Andrews, W. W.
Arthur, M. A.
Athy, L. F.
Bader, Glenn E.
Baker, Jerry D.
Ball, John Douglas
Barber, Thomas D.
Barbisch, J. B.
Barclay, Stewart
Barker, Alvin F.
Barksdale, Gerald L.
Barnes, R. H.
Bartow, Arthur I.
Bass, B. L.
Bassinger, William E.
Bean, Robert J.
Beeman, Keith R.
Beeth, Donald
Bell, Olin G.
Belton, Leslie O., Jr.
Benke, M. L.
Bennett, Roy F.
Benson, V. K.
Berg, G. A.
Berleth, W. H.
Bernatis, John D.
Bertram, A. C.
Bible, John L.
Bingham, W. W.
Bird, Ross H.
Black, J. P.
Blair, Ray H.
Blau, L. W.
Bledsoe, W. S., Jr.
Blevins, Paul
Bohannon, Milton A.
Book, L. R., Jr.
Boudreaux, Edward A.
Briard, Vernon E.
Briggs, Robert B.
Britt, J. A.
Brooks, James A.
Broussard, C. H.
Broussard, D. Frank
Brown, Andrew
Brown, E. E.
Brown, Hart
Brune, Leroy Charles
Bruyere, R. N.
Buckner, Guy O.
Bulhon, J.
Burke, William H., Jr.
Burkhalter, Howard Lee
Burkhead, Wayne Z.
Burt, W. H.
Butler, W. W.
Byers, John W.
Callahan, Janie L.
Campbell, H. H.
Capo, Roy R.
Carlisle, C. H.
Carlton, Dave P.
Carnes, William A.
Carter, Ray K.
Catchings, Robert F.
Chalmers, F. L.
Charrin, Paul
Charske, C. J.
Cheney, Robert H.
Child, V. E.
Christman, A. J.
Clark, George B.
Clark, Sherman D.
Clark, Wheaton C.
Clark, W. O.
Clevenger, M. A.
Clifford, Edward L.
Cloud, R. T.
Conwill, George E.
Cook, Jimmie P.
Cook, Paul C.
Coppedge, D. G.
Cornett, J. R.
Courtney, Cecil
Cram, Ira H.
Crary, James D.
Crowell, J. H.
Crusius, Milton W.
Culbertson, J. A.
Darden, David B.
Dauphin, W. D.
Deussen, Alexander
DeWoody, D. A.
Dierker, William E.
Doss, Miss Joe
Drake, Marvin E.
Dunaway, J. H.
Duncan, Newton O., Jr.
Dupree, Leon L., Jr.
Duty, Robert S., Jr.
Duval, Ned E., Jr.
Easterly, Herman, Jr.
Eby, J. Brian
Edwards, Charles E.
Ehrhardt, Henry L.
Evans, Eugene P.
Farren, Paul
Faudry, Ray E.
Fay, Charles H.
Feagin, Frank J.
Feather, W. R.
Fegan, George K.
Ferguson, Jack B.
Ferguson, Joe L.
Fielder, C. K.
Fish, Robert Dudley
Fishback, Joseph W.
Flatow, Tobias
Flude, John W.
Flynn, B. Michael, Jr.
Fohs, F. Julius
Francis, W. Douglas
Freel, J. F.
Frosch, A.
Frowe, Eugene
Fryer, Alan P.
Gaither, H. L.
Gallaway, R. L.
Gardner, Derry H.
Garrett, William M.
Germany, Clinton B.
Gibson, W. H.
Giezendanner, S. S.
Giles, Howard W.
Gill, O. P.
Girard, Harry J.
Glenn, E. J.
Goldstone, Frank
Gorman, D. Y.
Goss, Henry V.
Gould, Martin J.
Grace, Marvin
Graham, Floyd B.
Graham, John R., Jr.
Griffin, I..M. Jr.
Guiler, Mona D.
Hachenberg, Charles D.
Hafner, W.
Hale, E. M.
Hale, R. B.
Hall, T. O.
Hamil, A. B.
Hamil, Robert M.
Hamilton, W. Brooke
Hammial, L. L.
Hanahen, P. M.
Hans, Edward
Happel, Henry H.
Harbaugh, Allan W.
Harding, Norman
Harkins, Curtis P.
Harkins, T. I.
Harper, William Earl
Harrington, G., Jr.
Hartman, Jack T.
Hartman, W. M.
Hastings, James I.
Hawes, W. S.
Haynes, R. B.
Healy, John C.
Hebert, Harold C.
Heggy, Homer L.
Heintz, Karl O.
Hemmi, C. W.
Henderson, Homer I.
Hermont, Alfred J.
Hess, Edith May
Heying, Lorence J.
Hibbler, M. E.
Hill, E. Bruce
Hill, Joseph W.
Hilton, R. C.
Hinson, Cecil C.
Hoard, J. H.
Hobbs, Willis E.
Hocker, Otis B.
Hoeninghaus, F. A., Jr.
Hofacket, Owen L.
Holland, Edward H.
Holland, Sam B.
Holland, Taylor H.
Holley, Leman M.
Holmberg, Jean Martin
Hoover, H. L.
Hoover, J. W.
Horvitz, Leo

Howard, Ben R.
Howell, Lynn G.
Hubbard, Charles L.
Hubbert, M. King
Hudman, Vernon C.
Hudson, James D.
Hull, J. W.
Hunzicker, A. A.
Hurt, W. B.
Hutchinson, C. C.
Ingels, C. R.
Ivy, John S.
Jackson, G. L.
Jameson, John A.
Jett, J. E.
Johnson, Marn M.
Johnson, W. D.
Jones, E. E.
Jubran, Joseph R.
Judson, Sidney A.
Kannenstine, F. M.
Karlsdind, Don B.
Kaufman, Sidney, Sr.
Keese, James D.
Kennedy, Robert P.
Kenney, Teddy R.
Kent, Leon A.
Kepner, Thomas H.
Kimes, Albert
Kisler, Floyd
Klaveness, A.
Knouse, A. M.
Kohler, A.
Kokesh, F. P.
Koppel, David G.
Kouri, Barton H.
Krause, Fred W.
Kretz, R. L.
Kriegel, H. C.
Kubik, Kasmier D.
Kunkel, Turner L.
Ladner, A. L.
Lamb, George B.
Larue, James E.
Lau, Frank W.
Lavender, Gerald J.
Lawson, Royce Earl, Jr.
Lay, Roy L.
Lea, Norman
Lea, W. T.
Lee, W. B., Jr.
Leonardon, Eugene G.
Lewis, Ray C.
Lewis, Wendell L.
Long, Gebhard J.
Lundstrom, Fred L.
Lytle, T. M.
MacAllister, C. T.
Mackle, Vincent D.
Mann, Horace M.
Marr, John D.
Marsh, Albert P.
Marti, E. J.
Martin, E. C.
Martin, Sidney A., Jr.
Martyn, Phil F.
McCann, K. G.
McCollum, Burton
McDonnold, H. W.
McDowell, A. N.
McDuff, Milton A.
McFerron, George I.
McGee, John E.
McGowan, F. H.
McKelvy, W. H.
McNaughton, D. A.
McNeil, Walter A.
McReynolds, Gregg F.
McWilliams, Donald G.

Melton, D. P.
Miller, Arthur B., Jr.
Miller, Thomas J.
Millet, M. J.
Monkhouse, John R.
Montgomery, Geo. P., Jr.
Montgomery, J. C.
Moore, James A.
Moore, John H.
Moore, R. R.
Morrison, Clarence O.
Mounce, W. D.
Mounce, William P. Jr.
Mower, L. K.
Murray, Edward F., Jr.
Murrell, James T.
Myers, Charles E.
Nance, A. G.
Nelson, W. P.
Nettleton, L. L.
Neuman, L. J.
Newton, William H.
Nichols, J. B.
Noonan, W. G., Jr.
Nordling, Robert W., Jr.
Norman, Robert
Norris, C. G.
Nutt, W. T.
Ording, J. R.
Ostreim, R. N.
Paitson, Lloyd
Parker, Kenneth L.
Parker, L. A.
Parker, Richard H.
Parsons, Grant C.
Paschall, John P.
Patrick, H. G.
Patterson, W. L.
Pawley, Julian K.
Pemberton, William D.
Pena, Sam M.
Pfennig, Walter F.
Phelps, Kenneth D.
Pierson, Andrew L.
Pitts, J. B.
Poe, J. W.
Poland, V. K.
Pollard, Glen R.
Pollard, Jack C.
Pollard, William
Pollet, Arthur
Pope, Thomas T., Jr.
Popp, Frederick Wm. Jr.
Postma, G. W.
Powell, Paul B.
Prescott, H. R.
Rabensburg, Aubrey H.
Randolph, J. R.
Ratliff, Guy M.
Ray, Robert H.
Reed, Chas. F.
Reid, William, Jr.
Reivere, Romaine
Reynolds, F. F.
Rhodes, Joseph S.
Richards, George L.
Riley, James E., Jr.
Robinson, Charles L.
Rockwell, G. O.
Robinson, Edwin H.
Robinson, Leonard, Jr.
Rogers, Austin S.
Rolshausen, F. W.
Romberg, Frederick E.
Rookus, James D.
Rulfs, G. W., Jr.
Ruska, Walter E. A.
Russell, Stewart L.
Rust, W. M., Jr.

Sappington, Chester
Sargent, R. L.
Sasseen, John H.
Saville, W. G.
Sax, William A.
Schafer, Sidney
Schander, J. R.
Schmidt, Henry
Schmuck, R. H.
Schofield, G. A.
Scholl, Louis A., Jr.
Schorre, Barthlome
Schumacher, J. P.
Scott, David H.
Scroggs, James E.
Sears, Harold A.
Segal, Jerome Joe
Selig, A. L.
Sellers, Blake M.
Sellers, C. C.
Sellers, Clemille F.
Sharpe, John M.
Sheets, Martin M.
Shera, Frank W.
Sherar, E. S.
Sherar, Stuart
Shore, Harold F.
Showalter, Richard C.
Sims, Sam E.
Singer, Robert R.
Smith, A. E.
Smith, F. A.
Smith, H. C.
Smith, Harold B.
Smith, J. Angelo
Smith, Neal J.
Smith, Noyes D., Jr.
Somers, George B.
Speckels, Arthur W.
Spencer, Samuel A.
Spencer, J. S.
Stanford, Earl B.
Stauffer, Arthur L.
Steenland, N. C.
Stephens, Lester H.
Stommel, H. E.
Stone, Geo. B.
Stouse, Maurice J., Jr.
Stratton, E. F.
Summers, Frank B.
Sweet, R. C.
Tackenberg, Pieter
Talmage, E. W.
Talty, Russell H.
Taylor, Glenn B.
Taylor, Josiah
Taylor, W. Harlan
Teague, Norman P.
Terrasson, Paul Louis P.
Terry, Melvin C.
Terry, Russell D.
Thackston, Warren C., Jr.
Thomas, Dick L.
Thompson, K. C.
Thompson, Paul M.
Thompson, R. P.
Tucker, Robert L.
Turner, George R.
Turney, Maurice D.
Urban, L. M.
Urquhart, Edward H.
Van Auken, John A.
Vanderdoes, G. G.
Van Dusen, M. D.
Van Melle, F. A.
Vaughan, Leslie L.
Vernon, George H.

Vogel, Charles B.
Walker, James E.
Wallace, C. R.
Wallace, Frank R.
Wallace, James L.
Wasserman, Norvan Lee
Watt, J. S.
Weaver, Paul
Welboan, J. S., Jr.
Weston, Ray Franklin
White, S. A.
Whitten, Stephen E.
Wier, Joe R.
Wilber, Roscoe C., Jr.
Wilcoxon, Robert B.
Wilkens, Lucian M.
Williams, C. E.
Williams, E. Darrell
Wilson, James M.
Wilson, William H.
Winter, Geo. W.
Wolf, Alexander
Wright, Fred E.
Wright, James F.
Wright, Ray H.
Wu, Chang Sheng
Wynn, Robert O.
Yokubaitis, A. C.
Zagst, Edward F.
Zavoico, Basil B.
Zenor, H. M.
Zimmerman, C. C.
Zirbel, N. N.

Irving
Batson, James B.
Campbell, William M.
Carson, Roe W.
Hefferman, William H.
Horn, Russell E.
Luehrmann, William H.

Jacksboro
Tweddell, Ralph D.

Jacksonville
Huff, Allan L.

Kermit
Matson, Don Dean
Patch, James R.

Kingsville
Hume, Ernest H.
Kitchens, J. T.
Starr, A. G.

Lamesa
Baer, Karl E.
Pilcher, Ned
Scott, Clarence E.
Shamblin, W. E.
Smith, Edward E., Jr.

Laredo
Deschner, Anton H.
McMahan, Robert F.

League City
Smiers, Herman L.

Liberty
McKinley, Wm. D.

Littlefield
Hartin, Curtis L.

Livingston
Lilley, Charles C.

Lockhart
Bernard, Curtis R.

Lockney
Thomas, Virgil O.

Lubbock
Ebert, Charles E.
Epperson, R. S.
Garrison, Phil H.
Gregston, G. D.
Hughes, J. C.
Kaufmann, Charles H., Jr.
Kendrick, Harold L.
Klaus, Hellmut
Libby, Frederick E.
Logan. W. B.
Mataya, Jack L.
Morrison, Malcolm S.
Pentz, Harold H.
Richardson, H. K.
Scudday, Edwin R.
Smith, C. C.
Valder, Clayton S., Jr.
Wigley, Lawrence H.
Yuzbick, R. J.

McKinney
Barmore, Clarence E.
Milford, Richard D.

McLeod
McLeod, Curtis R.

McQueeney
Haines, C. E.

Midland
Arick, M. B.
Bailey, J. J.
Barker, Addison S.
Barnes, A. L.
Blakeman, Edmund R.
Borys, Edmund
Brock, John L.
Broyles, Robert W.
Burton, Raiford H.
Bychok, Victor
Coburn, Haskell
Conover, George E.
Cornell, R. B.
Cornish, Lou G.
Daly, John W.
Danz, D. W.
Dawson, L. Decker
DeJournette, R. D., Jr.
Dennis, Terence E.
Dial, James B.
DiGiulio, Fred J.
Domenico, S. Norman
Drachenberg, W. A.
Edwards, Jack W.
Epperson, Louis J.
Farley, James F.
Feather, V. G.
Ferree, Ray J.
Fischer, Leon
Forbes, C. B.
Forward, Fred
Gaines, Betty
Gibbs, Kenneth E.
Gibson, George R.
Gilbert, Kennis W.
Grafton, W. Dean
Grimm, G. A.
Hake, Stanley L.
Hammel, Warren R.
Hardison, Stanley G.
Hewitt, Jack E.
Hinton, B. H.
Homan, W. L.
Horton, J. D.
Hovey, Gene Dana
Ittner, Frank
Jackson, O. B.
Jasper, Walter E.
Johnson, Billy C.
Johnson, Lester H.
Jones, Stuart A.
Jordan, E. A.
Kangas, Reino
Kaukonen, E. K., Jr.
Keffler, Joseph W.
Kerr, Charlton
Lambert, G. D.
Mace, H. G.
Martin, G. W.
Mason, Marshall, Jr.
McFarlane, John F.
Mehringer, A. P.
Michaelson, Louis H.
Mims, Robert L.
Moore, Arthur A. Jr.
Morehead, Jack N.
Murphree, David B., Jr.
Myers, Jack W.
Neill, Everett D.
Noble, H. J.
O'Brien, William R.
Owings, B. F.
Ownby, Byron
Page, C. Newton
Park, Lee B.
Park, Noel R.
Parker, G. A.
Partridge, C. Roland
Patterson, H. F.
Paul, Kenneth W.
Pluta, Joseph S.
Porter, James C.
Rainey, Richard H.
Ray, Bill B.
Ray, Lilburn B.
Reed, Paul C.
Reel, C. E.
Reeves, W. A.
Roller, John C.
Ross, W. T.
Rosser, Billie A.
Rumsey, Paul T.
Rustamier, Jack W.
St. Clair, D. W.
Shettle, George O.
Shock, Lorenz
Shoup, Geo. J.
Sorgenfrei, D. C.
Stites, Richard L.
Stone, Robert C.
Swanson, Jack G.
Swords, H. L.
Turner, Dale E.
Uhrig, Leonard F.
Unger, E. E.
Viterbo, Verne D., Jr.
Voelker, H. L.
Walker, Wm. N.
Ward, J. H. E.
Warren, R. P.
Welcker, Fred
Wells, R. G.
West, James L. Jr.
Winter, Niles B.
Woods, James Douglas
Wright, Jesse W. Jr.
Wright, Randolph E.

Monahans
Diveley, Paul R.

New Braunfels
Scott, M. D.
Watts, Evan

Odessa
Bugby, Roger A.
Davis, L. A.
Houston, Grafton, Jr.
Kilborn, Mrs. J. M.
Kilborn, Joseph M.
Patterson, Sam W.
Pechacek, Emil F.
Thurber, C. H.
Vlasak, Frank E.
Walling, F. Rex, Jr.

Orange
Arsenault, Charles A.
Hargest, Thomas S.
Thompson, W. A.

Ozona
Clement, Alvin H.
Frank, Harold Roy, Sr.

Paris
Whitaker, Richard O.

Pecos
Moran, Ray O.
Opitz, E. E.
Ruhlen, W. W.
Toliver, Billie A.

Perryton
Alexander, Michael, Jr.
Harvill, Robert S., Jr.
McMahan, J. R., Jr.

Plains
Compton, Lee

Plainview
Foster, Floyd F., Jr.
Goodfellow, Robert T.

Port Arthur
Branham, W. H.

Riverside
Weinzierl, J. F.

Rockport
Glazener, George S.

Rosenberg
Foote, W. L.
Neese, U. E.
Swanson, Marion T.

San Angelo
Beesley, Stratton W.
Green, Howard W.
Rabensburg, N. J., Jr.
Smith, Billy G.

San Antonio
Allen, Thomas L.
Bartel, Edwin
Bennett, Elwin
Bissett, Clark
Carter, Roland H.
Cook, John C.
Crawford, Paul D., Sr.
Crawford, W. L.
Dawson, Herbert M.
Dinkins, Henry H., Jr.
Donnelly, V. T.
Drews, Theodore E.
Edmonson, J. W. E.
Gragnon, Joseph N.
Hannum, William L.
Hargis, A. V.
Howell, John L.
Hunzicker, Vernon J.
Kelley, W. W.
Langford, Eldon W.
Lewis, Eugene T.
McMillen, Ralph E.
Mitchell, Robert L.
Moore, Marion J.
Moore, W. Lee, Jr.
Narvarte, P. E.
Ohman, John
Parr, J. O. Jr.
Petty, Dabney E.
Petty, O. Scott
Phillips, Clifton
Pratt, R. B.
Proctor, John L.
Rudolph, P. J.
Russell, Jim
Schmidt, K. H., Jr.
Smyrl, H. B.
Snyder, Charles W.
Souther, J. B.
West, Thomas S.
Wright, J. Dexter

San Juan
Woodyard, Kenneth C.

Seagraves
Bollheimer, Paul A.

Sealy
Felcman, Frank L.

Seguin
Blumberg, Roland K.

Seminole
Goodgame, Paul B.
Kehoe, Charles A.

Seymour
Vandegaer, Cecil H.

Sherman
Hendricks, J. L.
Robertson, Glenn
Schiflett, H. L.

Sinton
Agerton, William D.
Ramzinsky, G. D.
Shear, J. N.
Stacy, E. L.
Tidwell, Ellis M., Jr.

Slaton
Heard, James R.

Smithville
Grizzell, Edward I.

Sweetwater
Lemaster, Randall R.

Three Rivers
Cocovinis, Dimitri B.

Tyler
Brooks, O. D.
Flowers, Jack J.
Graham, Robert C.
Hadaway, W. R.
McCutchen, Edgar O.
Moore, D. B.
Schuller, Jerome A.

Uvalde
Rasco, William A.

Waxahachie
Shackelford, L. L., Jr.

West Columbia
Leatherwood, H. D.

West Orange
Autrey, Charles B.

Wharton
Brown, Robert L.

Whitesboro
Ivey, James R.

Wichita Falls
Bradley, Joe R.
Burchett, Charles T., Jr.
Crain, Robert A.
Gilmore, John A.
Harris, Alfred H., Jr.
Harvey, William P.
Mayfield, W. I.
McReynolds, Oliver B., Jr.
Mitcham, Frank M.
Reynolds, E. E.
Sparks, James W.
Warren, Kenneth A.
Weeth, Chas. A.
Whitney, Vernon E.

Woodville
O'Brien, S. D.

Yoakum
Adams, Hugh M., Jr.
Hall, Frederic C.
Love, Perry R.
Maeker, Orville L.
Murphy, Robert E., Jr.
Spence, H. C., Jr.
Thompson, Jay F.

UTAH

American Fork
Hansen, Don A.
Sargis, S. G.

Bountiful
Mabey, Don R.

Cedar City
O'Toole, W. L., Jr.

Green River
Schuster, Gerhardt H. W.

Ogden
Fowles, George R.

Salt Lake City
Bauer, Robert W.
Cengiz, N. R.
Cherry, Charles L.
Cook, Kenneth L.
Hayes, Junius J.
Hobbs, T. E. (Jack)
Kim, Yon-Su
Lacy, R. J.
Larsen, Kenneth W.
Marquardt, Carlton M.
Murphy, William O., Jr.
Peterson, V. E.
Resley, Ray Chester
Storch, Robert H.
Whipple, R. W.

Vernal
Garrison, Jerry E.

VIRGINIA

Arlington
Kaiser, Geo. B.

Fort Belvoir
Smitherman, Lynn A.

Mineral
Smith, A. R.

Norfolk
Moore, L. E.

WASHINGTON

Quincy
Neibauer, Herman

Seattle
Bowlby, C. W.
Foster, Robert J.
Kamitchis, James E.
West, S. Stewart

WEST VIRGINIA

Point Pleasant
Kell, James A.

Princeton
Straley, H. W., III

WISCONSIN

Gile
Machesky, Lawrence F.

Madison
Belshe, John C.
Hinze, William J.
Mack, John W., Jr.
Meyer, Robert P.
Rose, John C.
Sumner, J. S.
Thiel, Edward (Carl)
Weart, Wendell D.
Woollard, George P.

Milwaukee
Chenoweth, Wm. C.
Kurfess, James A.

WYOMING

Buffalo
Blaire, Donald H.

Casper
Bone, R. M.
Brooks, William T.
Brow, LeRoy E.
Cohick, Kenneth S.
Dingman, M. H., Jr.
Early, Paul M.
Ellis, George L.
Erickson, John W.
Faust, Samuel Ray
Fenwick, Willis H.
Fletcher, Calvin D.
Gilkison, Don
Hawkes, W. H.
Hawthorne, W. W.
Heim, Jean W.
Hopkins, James S.
Howes, Thomas B.
Jackson, Rodney W.
Kemeny, Daniel J.
Kern, Marshall K.
Koch, Barry Walter
Kundert, Karl H.
Lake, Charles L.
Larguier, L. J.
Meade, George N.
C. F. Moore, Jr.
Parke, Morton L. Jr.
Parks, Robert R.
Pauly, Harold P.
Petsoff, George J., Jr.
Roberts, Grant M.
Roberts, Homer E.
Sawyer, Noah C., Jr.
Smith, Charles B.
Spalding, Carlton T.
Walczak, Michael J.
Wells, Wm. E.
Wilson, Thomas C.
Winfrey, D. B.

Cheyenne
Brown, David L.
Chase, Gordon W. (Mrs.)
Eitzman, Edward T.
Head, Paul A.

Cody
Goetter, John

Douglas
Lawrence, Eugene D.
Tipton, Dee LeRoy

Gillette
Barry, Kevin M.

Green River
McCuistion, Robert G.
Watson, Richard L.

Guernsey
Hollingsworth, James C.
Seward, Franklin A., Jr.

Lander,
Litwinowicz, V. K.

Laramie
Romney, Carl F.
Withstandley, Victor, III

Lusk
Pierce, Jack M.

Newcastle
Martens, Willis P.

Powell
McLeod, Curtis R.

Rawlins
Dallison, Sam James
Johnston, Frank M
Mount, Thomas M.
Taiclet, Daniel A.

Riverton
Sullivan, Daniel H.

Rock Springs
Horn, Wilbur M.

Thermopolis
Cooke, Samuel C., Jr.
House, H. M.

Torrington
King, V. Hugo

Worland
Chronister, Bill W.
Gartner, Robert Josef
Roripaugh, Chas. C., Jr.
Walz, Harry B.

FOREIGN

ALASKA

Barrow
Brewer, Max C.

ALGERIE

Alger
Beer, Fritz R.
Cholet, Jacques
Ortynski, H. I.

ARABIA

Dhahran
Beverly, Burt, Jr.
Garvey, Thomas A.
Hotchkiss, H. C.
Seager, O. A.
Spivey, Sherman R.
Storm, Alfred E.
Zimerman, Sam

ARGENTINA

Buenos Aires
Binetti, Vincente
Martin, Rodolfo
Orellana, E. I.
Valentini, Italo Americo
Vila, Fernando

Haedo
Rey, Pedro

Mendoze
Buttini, Bernardino E.

Rosario
Gurmendi, Juan C.
Llorden, J.

Santa Fe
Berros, S. A.
Munoz, Nobel

Sta Cruz
Breton, Jorge M.

AUSTRALIA

Canberra
Smellie, D. W.

Mortdale
Jeffries, F.

New South Wales

Sydney
Marshall, C. E.

Victoria

Melbourne
Garrett, Maxwell J.
de Groot, Raymond J. P.
Milstein, Mark
Wood, F. W.

West Brunswick
Smith, Edward R.

AUSTRIA

Hallein
Schubert, Herman

Salzburg
Kunz, Bruno F. J.

Vienna
Woitsch, Otto

BELGIAN CONGO

Costermansville
DeBremaecker, J. C.

BELGIUM

Bruxelles
Brognon, G.
Evrard, Pierre

BORNEO

State of Brunei
Balmforth, D. M.
Romeijn, C.
Schut, R. H. T.

BRAZIL

Belem
Koch, Herman J.
Linwell, Martin V.
Nery, Raymundo
Stair, Robert Y.

Maranhao
Assis, Waldemar De A.

Natal
Mota, L.
Rusch, Peter J.

Rio de Janeiro
Eichelberger, A. M., Jr.
Long, James A.
Oddone, D. S.

Salvador
Urrutia, Carlos, II

Sao Luiz
Floyd, Fernando

Sao Paulo
Arroyo, Albino

BRITISH WEST INDIES

Trinidad
Baxendale, L. A.
Geldart, Lloyd P.
Harvey, A. G.
Levorsen, Robert I.
Mett, Dennis R.
Nock, J. R.
Northwood, E. J.

CANADA

Alberta

Bashaw
Block, Jacob

Bassano
Bruce, Barton C.

Burderheim
Kittlitz, Raymond S.

Calgary
Agnew, Hinds
Alvey, G. C.
Angus, W. R.
Austin, Harold T.
Axford, D. W.
Aydinoglu, M.
Babb, John J.
Badgley, Peter C.
Baillie, Wilfred
Baker, Malcolm E.
Bannister, Wm. E.
Baxter, John C.
Bearden, Carl D.
Beck, A. F.
Bickel, Harold C.
Bigelow, Donald V.
Bixby, Robert H.
Black, William D.
Blakely, W. E.
Blundun, G. J.
Box, F. E.
Brannian, Ross E.
Brennan, D. F.
Brockway, L. I.
Brooks, Robert H.
Brotherhood, G. Roy
Burns, J. L.
Campbell, Everett L.
Campbell, T. A.
Cathey, J. A.
Chapman, C. J.
Chesher, C. E.
Chomel, Dominique D.
Christie, Norman J.
Clark, Earl
Claus, Spencer
Clifton, Frank
Cook, E. T.
Coote, George F.
Copeland, R. J.
Coupland, Robert W.
Creasey, Ernest W.
Dame, Andrew A.
Davis, R. E.
Deabler, Geo.
Denton, Eric R.
Dissler, Ernest W.
Doe, Robert
Downey, Hugh P.
Dunlap, A. D.
Elias, William H.
Erickson, E. L.
Farmilo, Alfred W.
Farrell, Patrick J.
Ferrell, George D.
Fickinger, D. E.
Frasher, James H.
Freeburg, John J., Jr.
Fuller, John C. J.
Gacek, Walter F.
Gallacher, John D.
Galloway, John O.
Gardner, J. W.
Gerrard, J. A. F.
Gray, Henry Douglas
Green, Thomas H.
Grinsfelder, Donald
Halbrook, T. A.
Hale, F. A.
Hale, John D.
Hamilton, J. J.
Hannon, N. M., Jr.
Harding, R. N.
Hayes, James O.
Hess, Gordon R.
Hinson, James M.
Hobman, Richard J.
Hohag, Walton H., Jr.
Holland, R. D.
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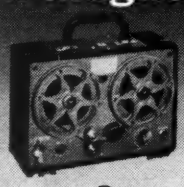

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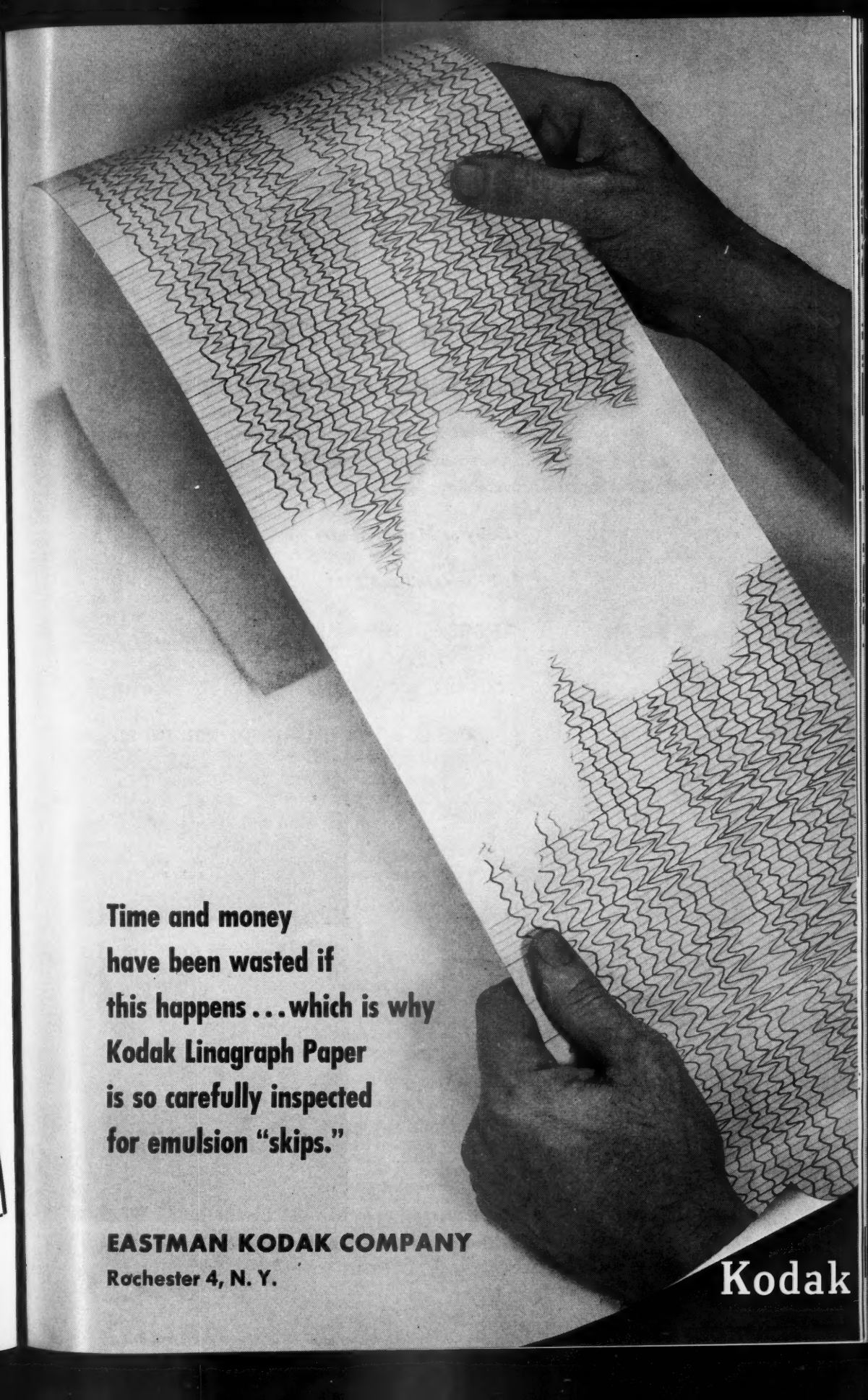
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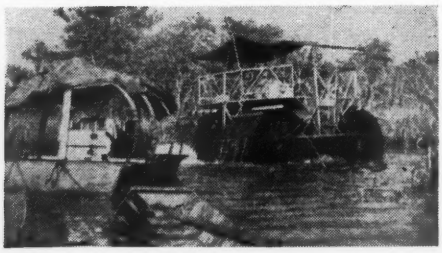

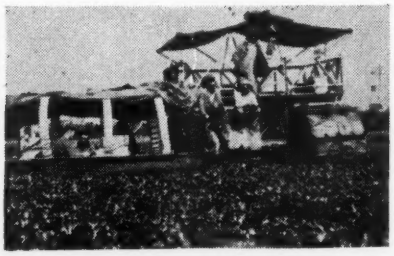

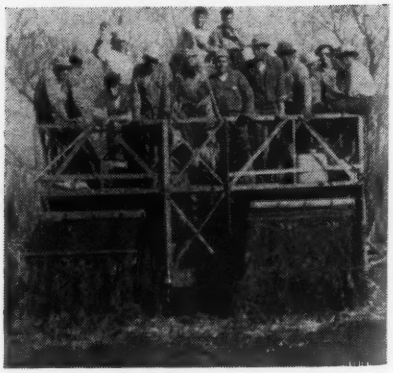

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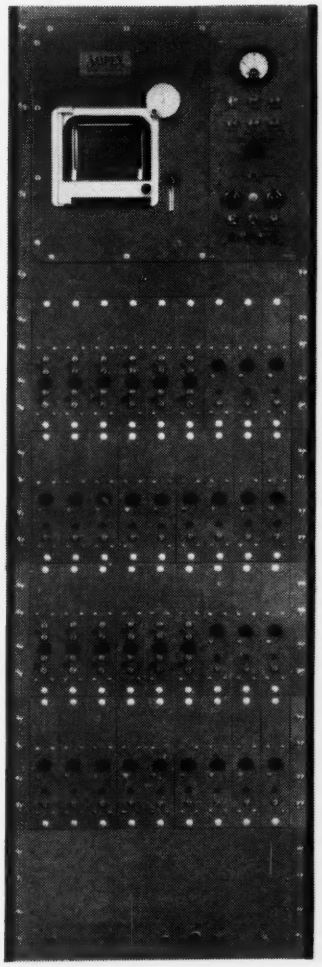

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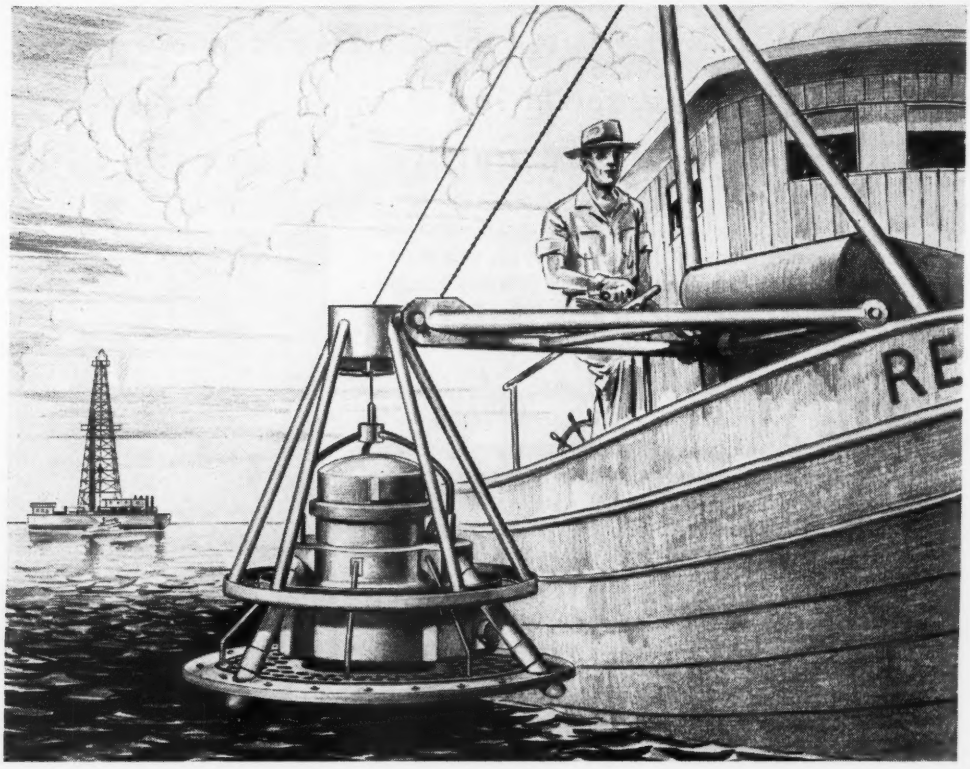

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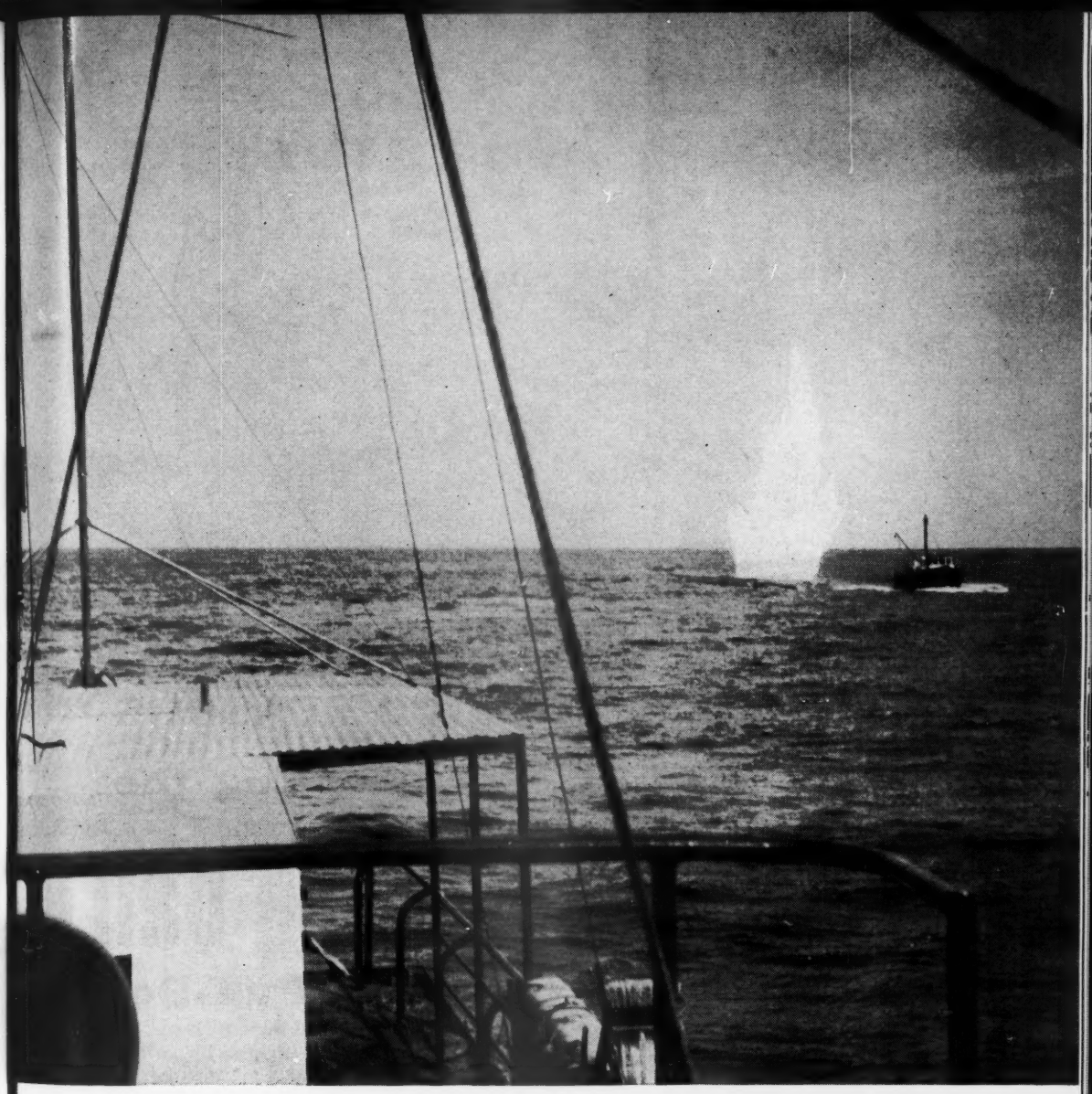

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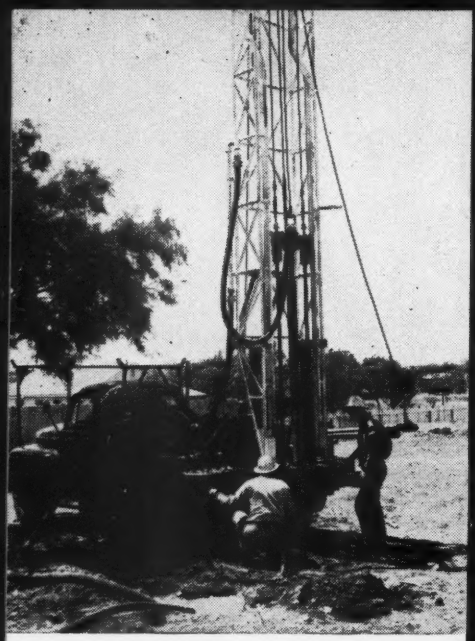

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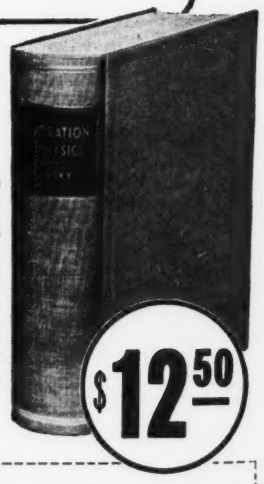

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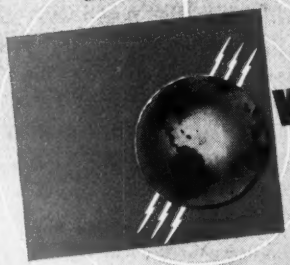

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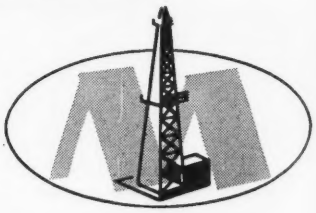

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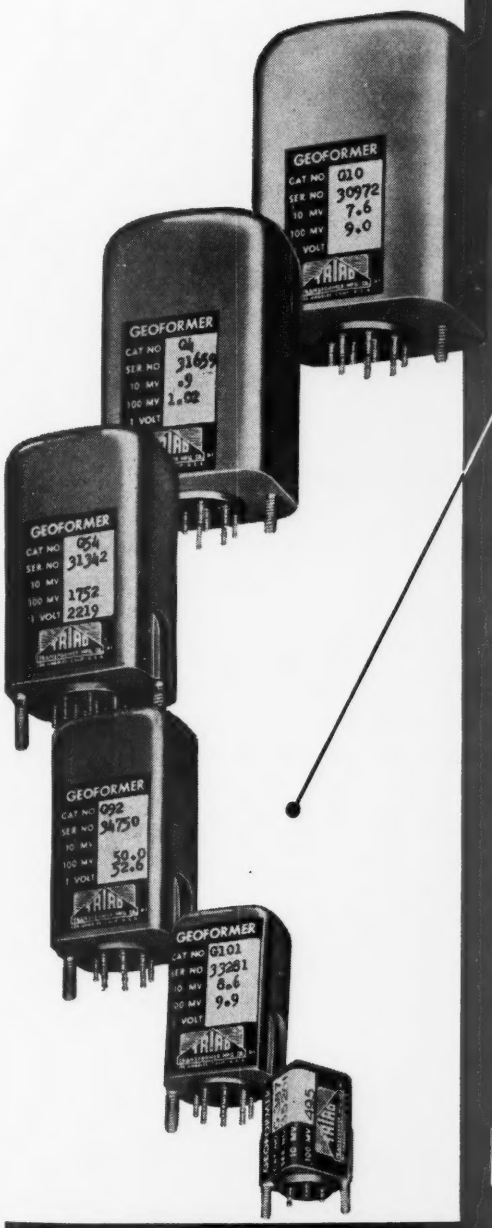

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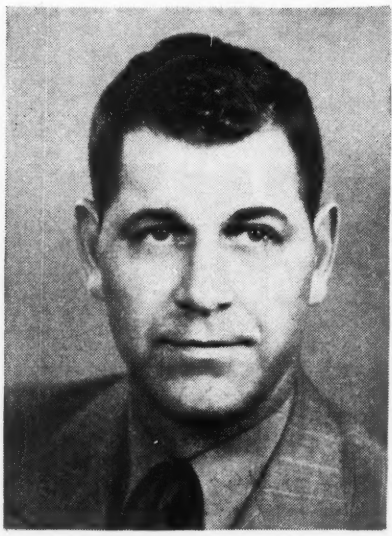

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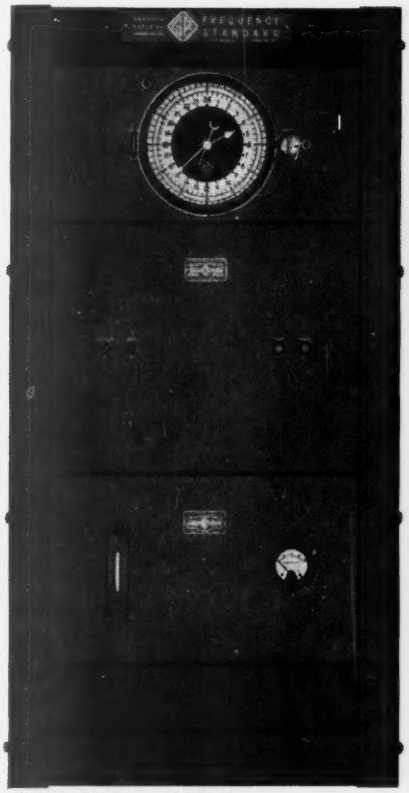

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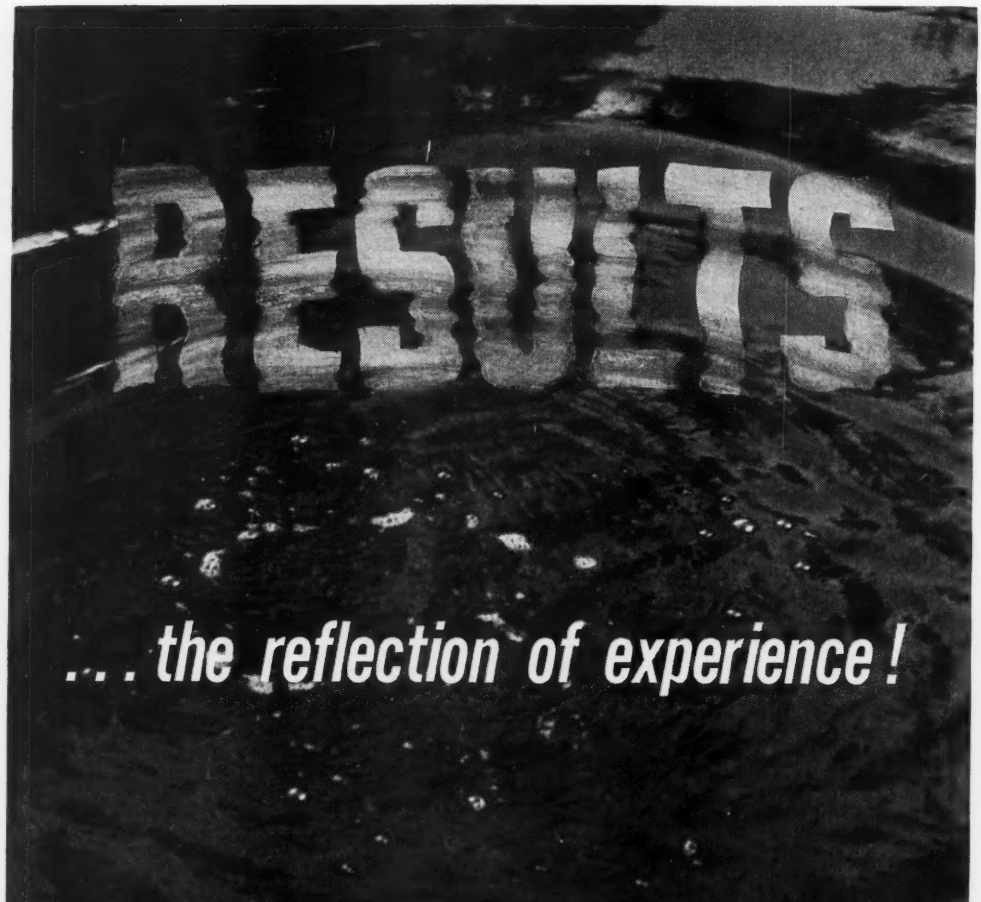
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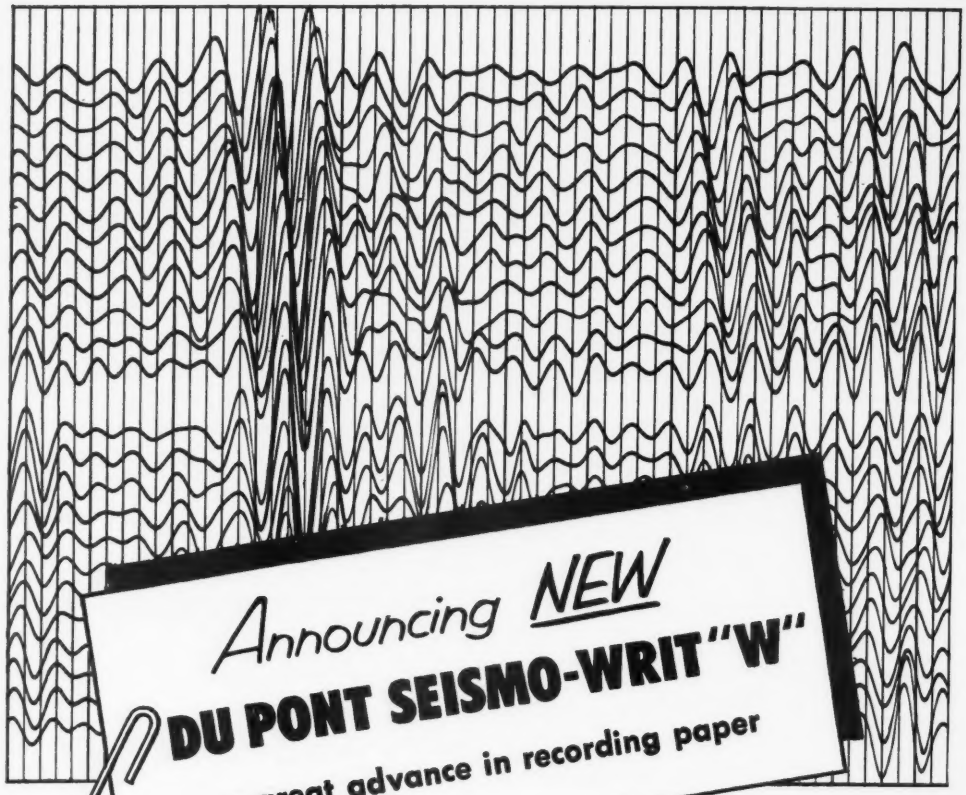

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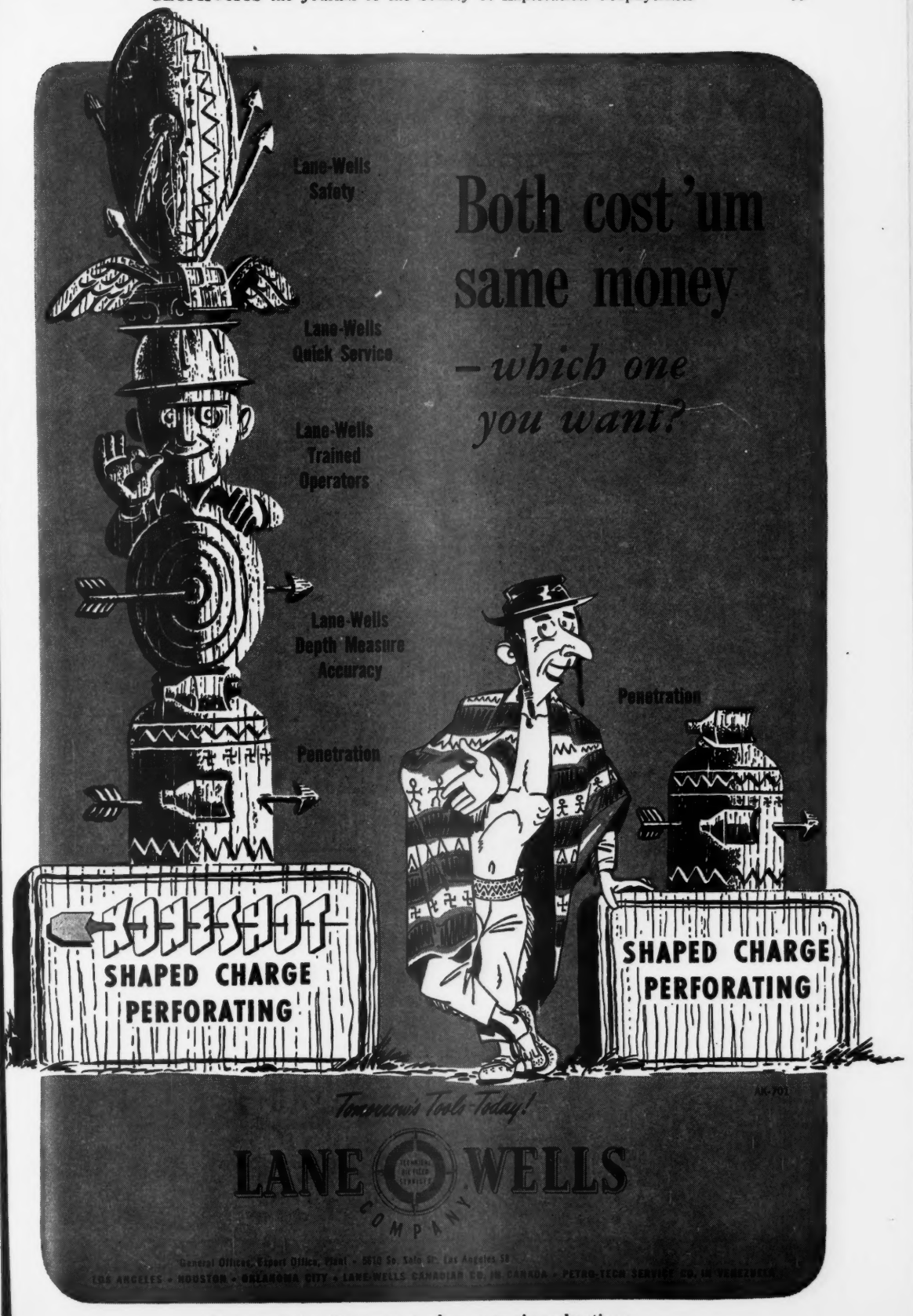
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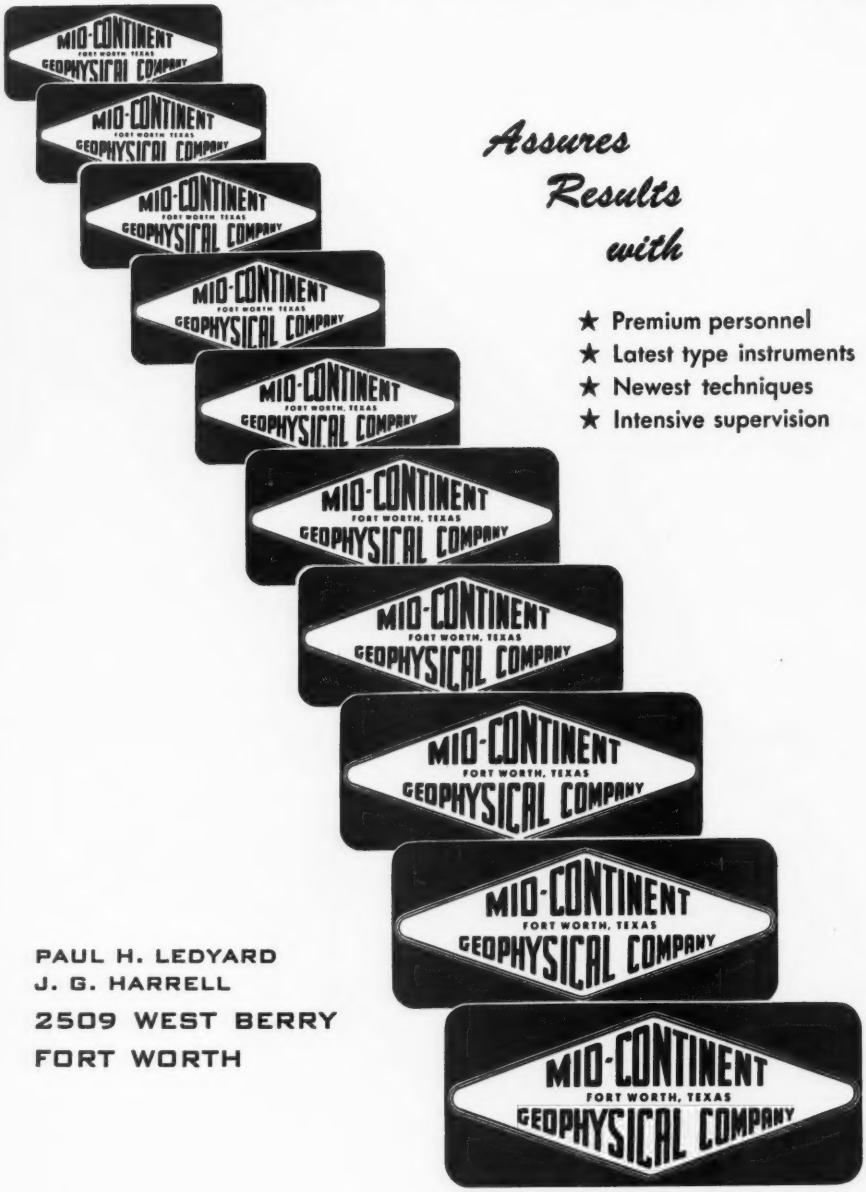

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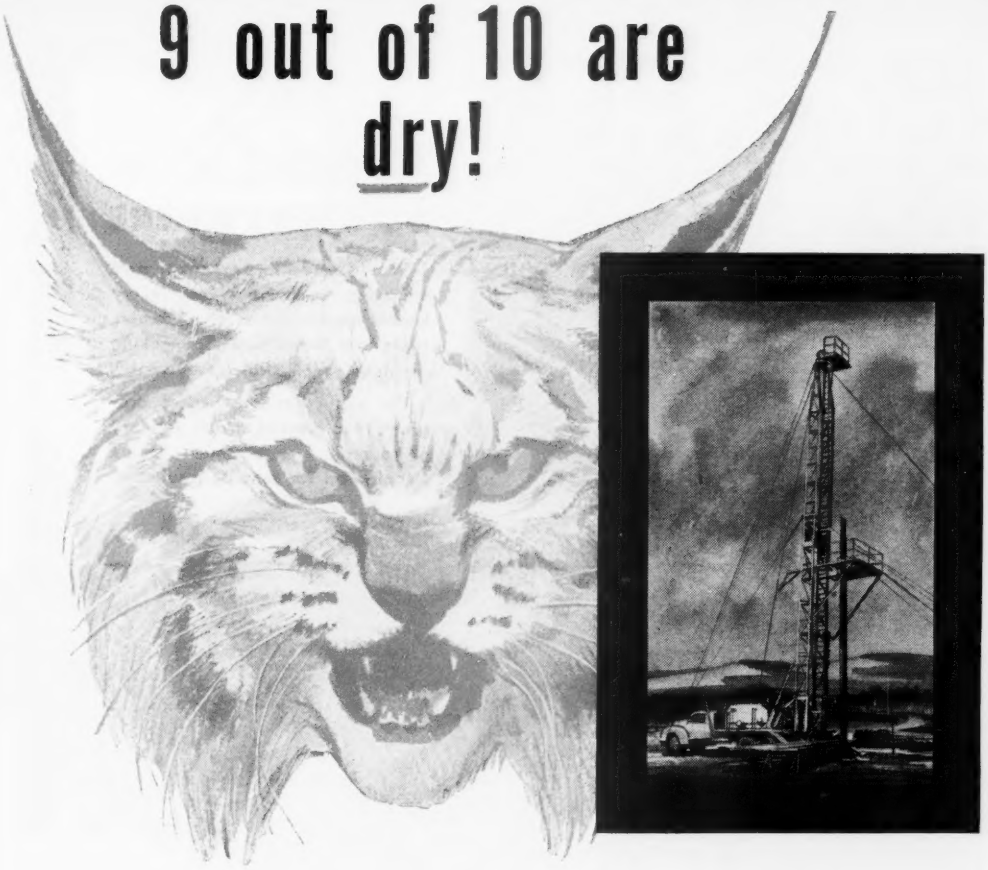

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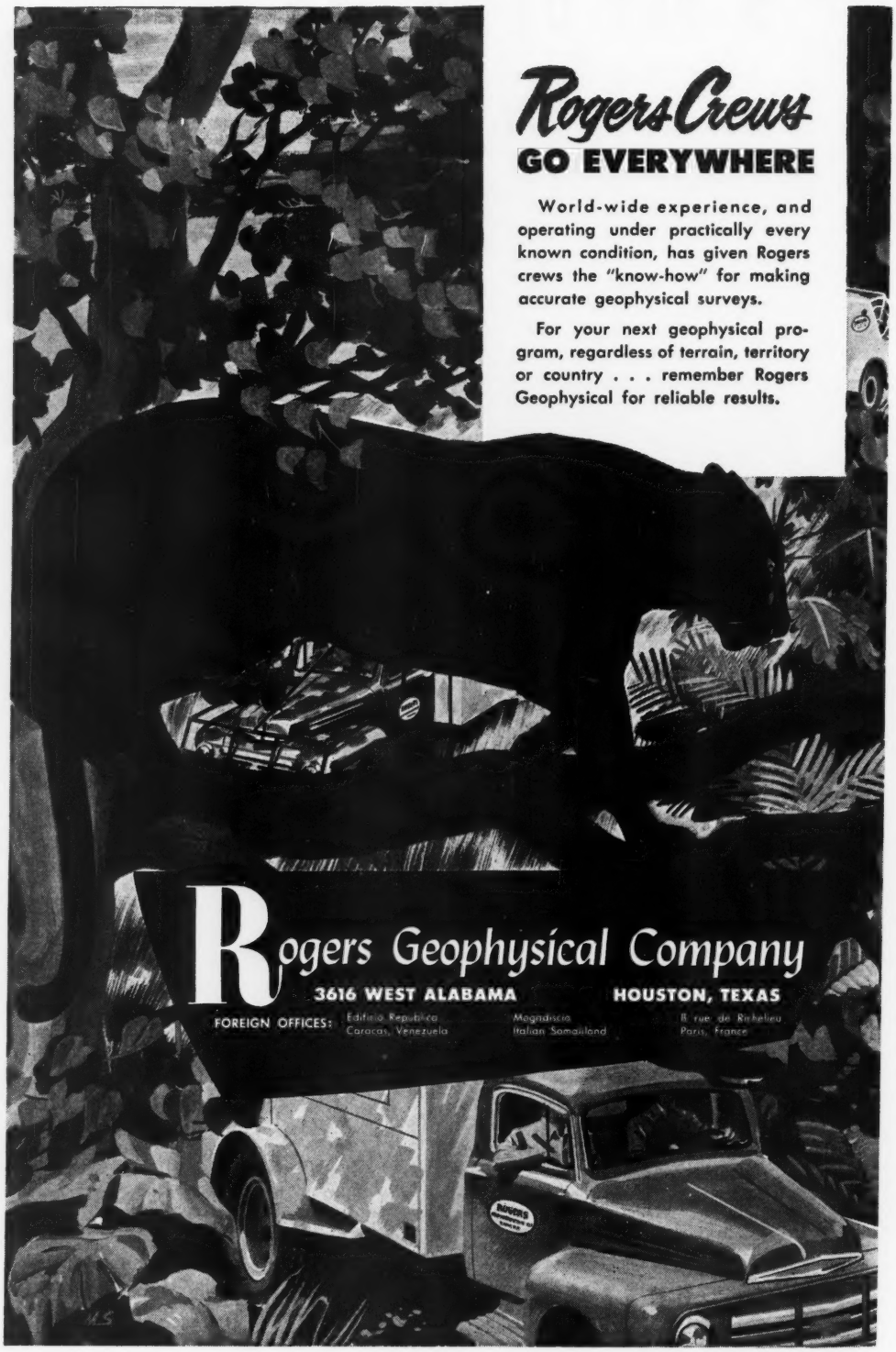
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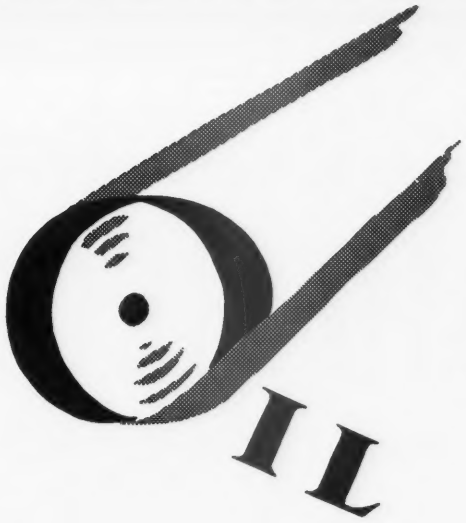

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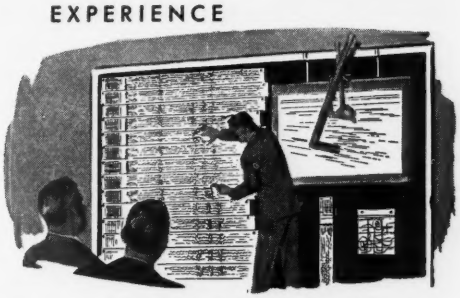

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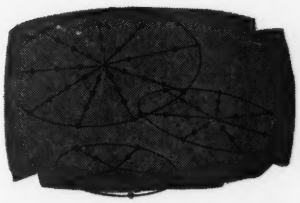

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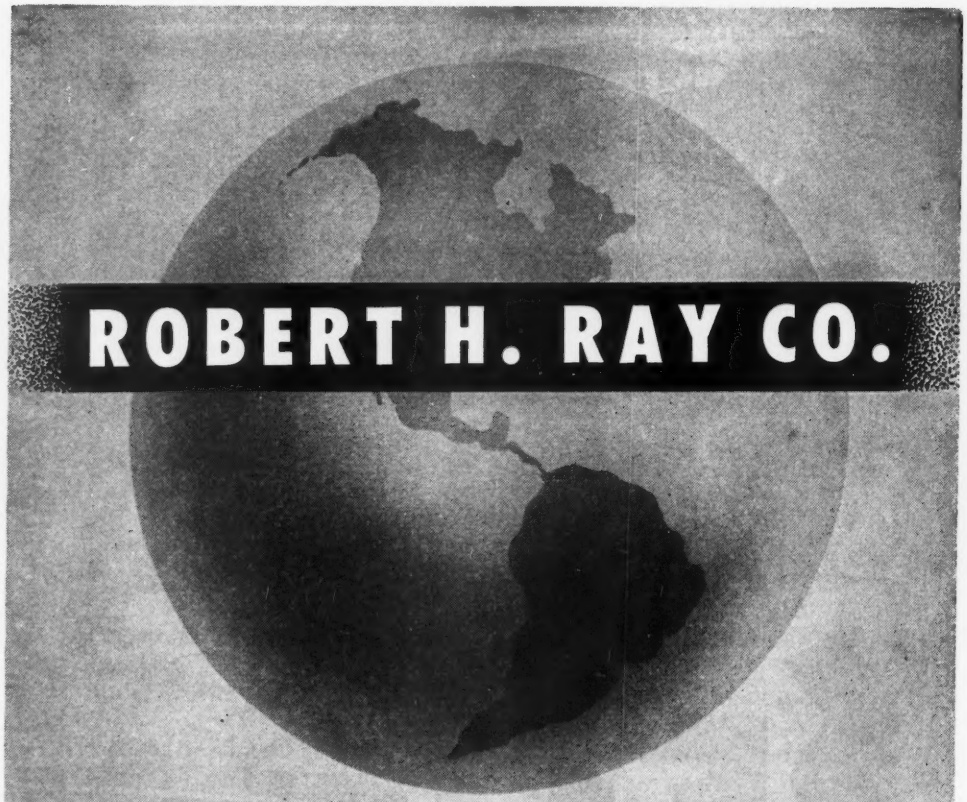

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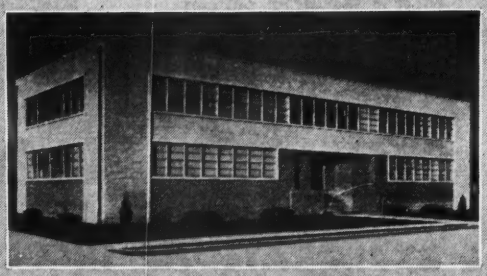

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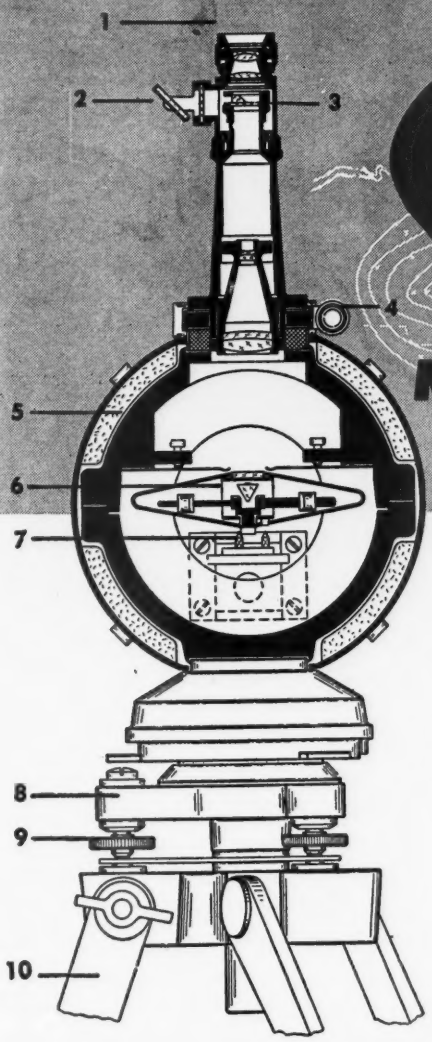

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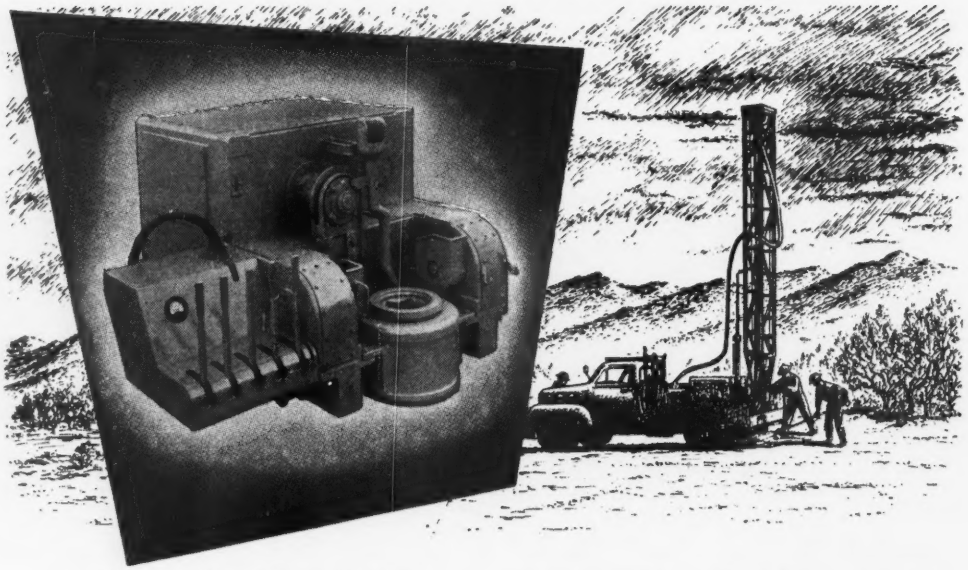

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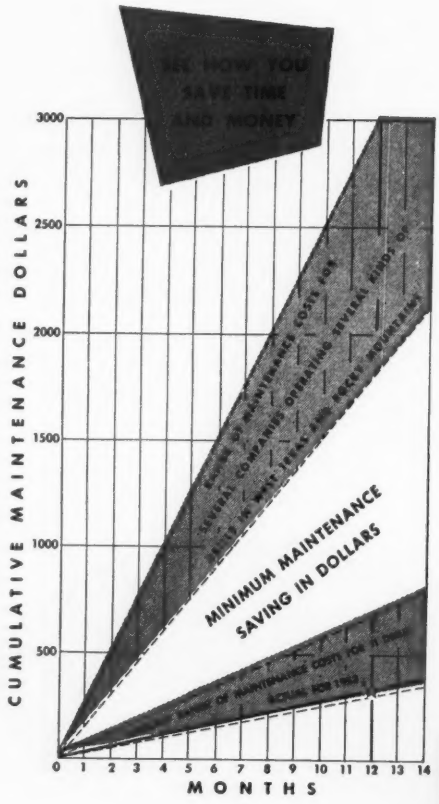

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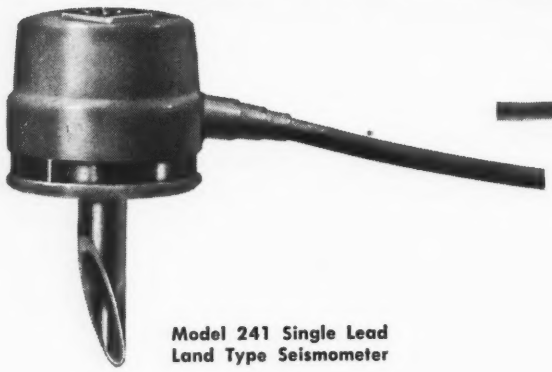

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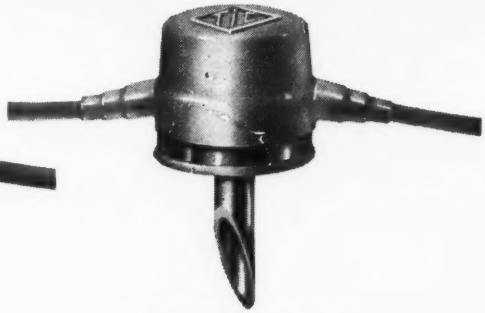

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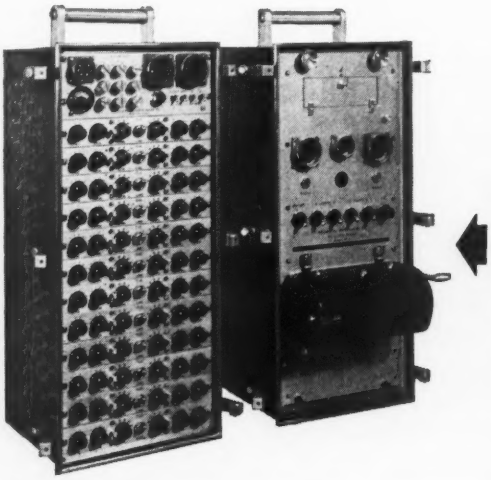

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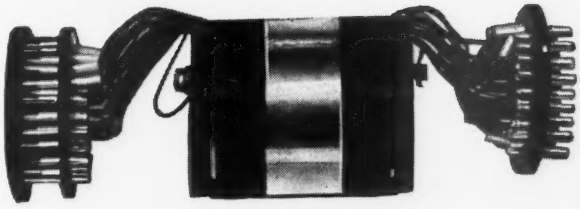

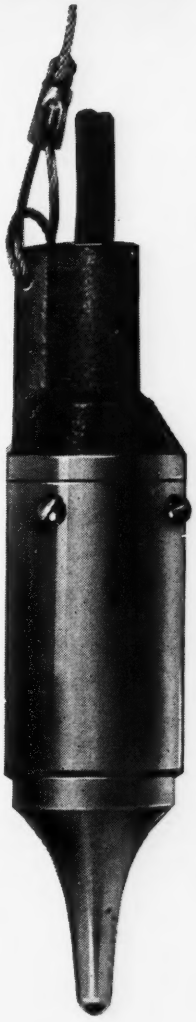

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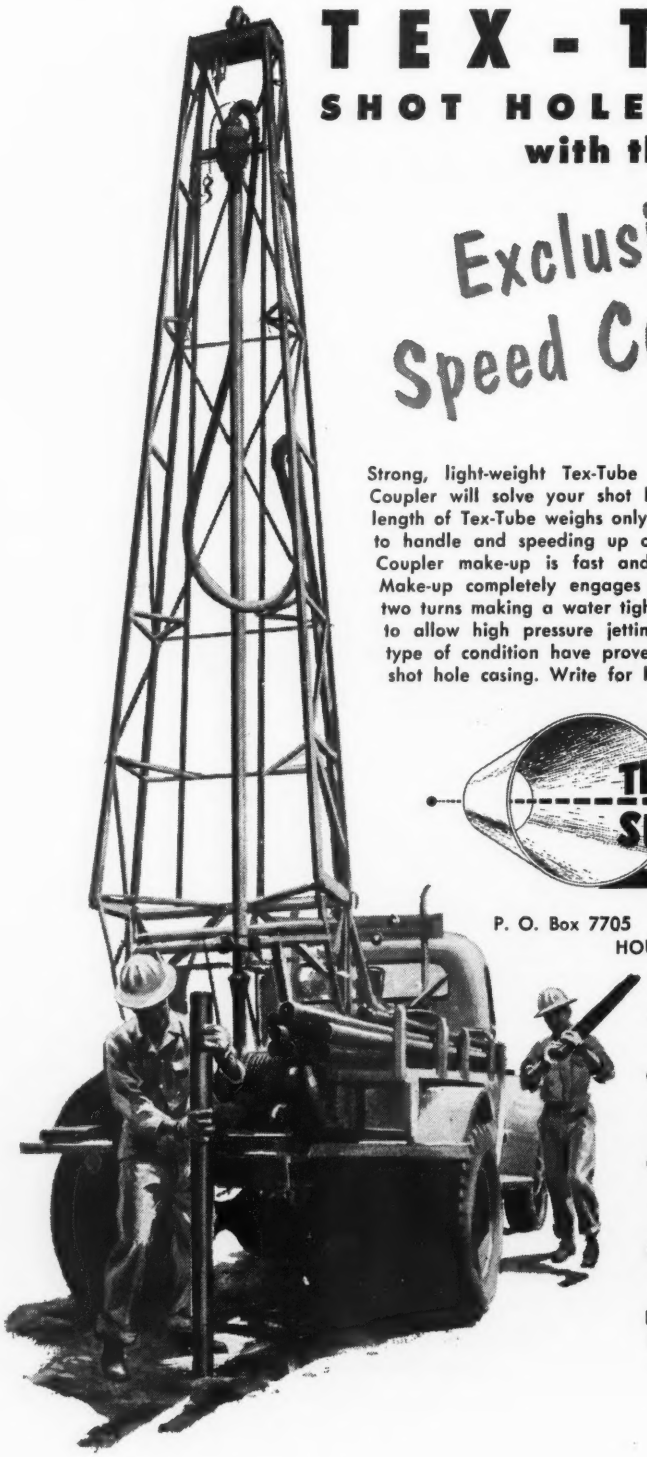

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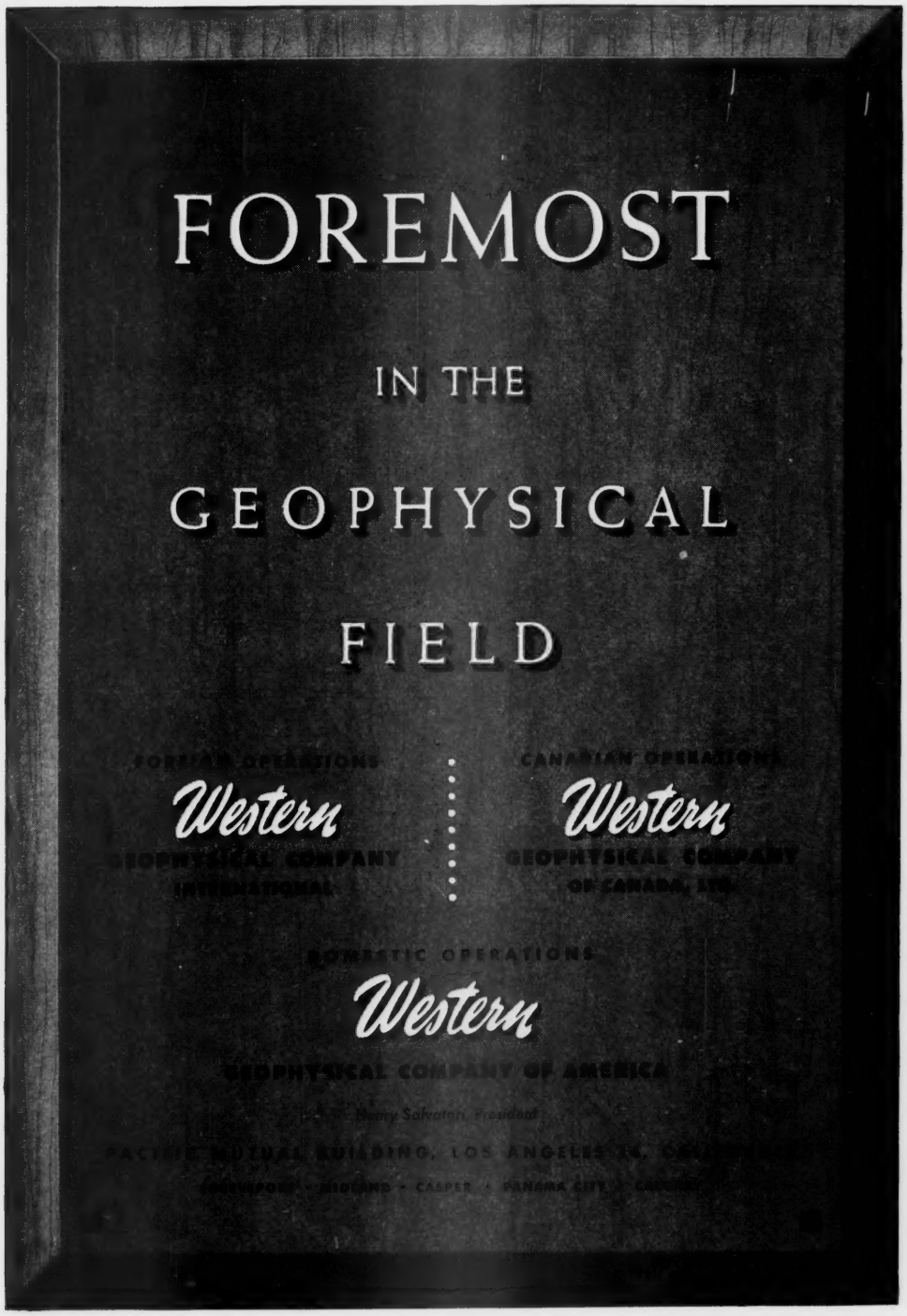
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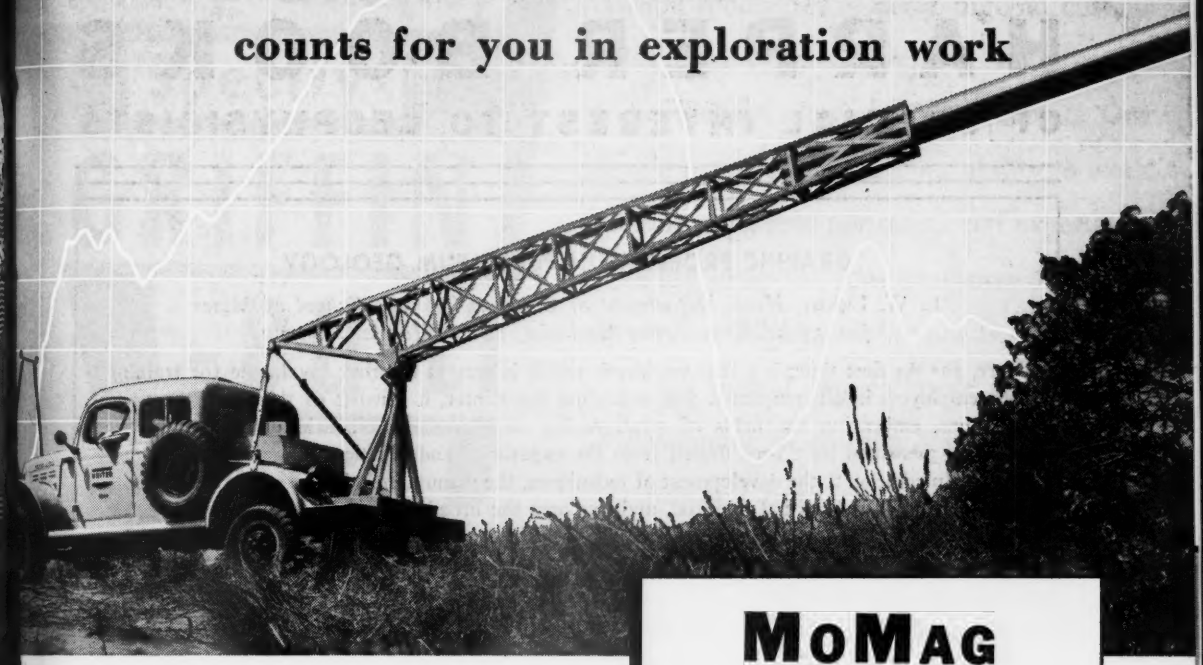

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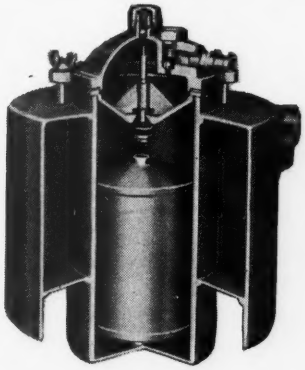

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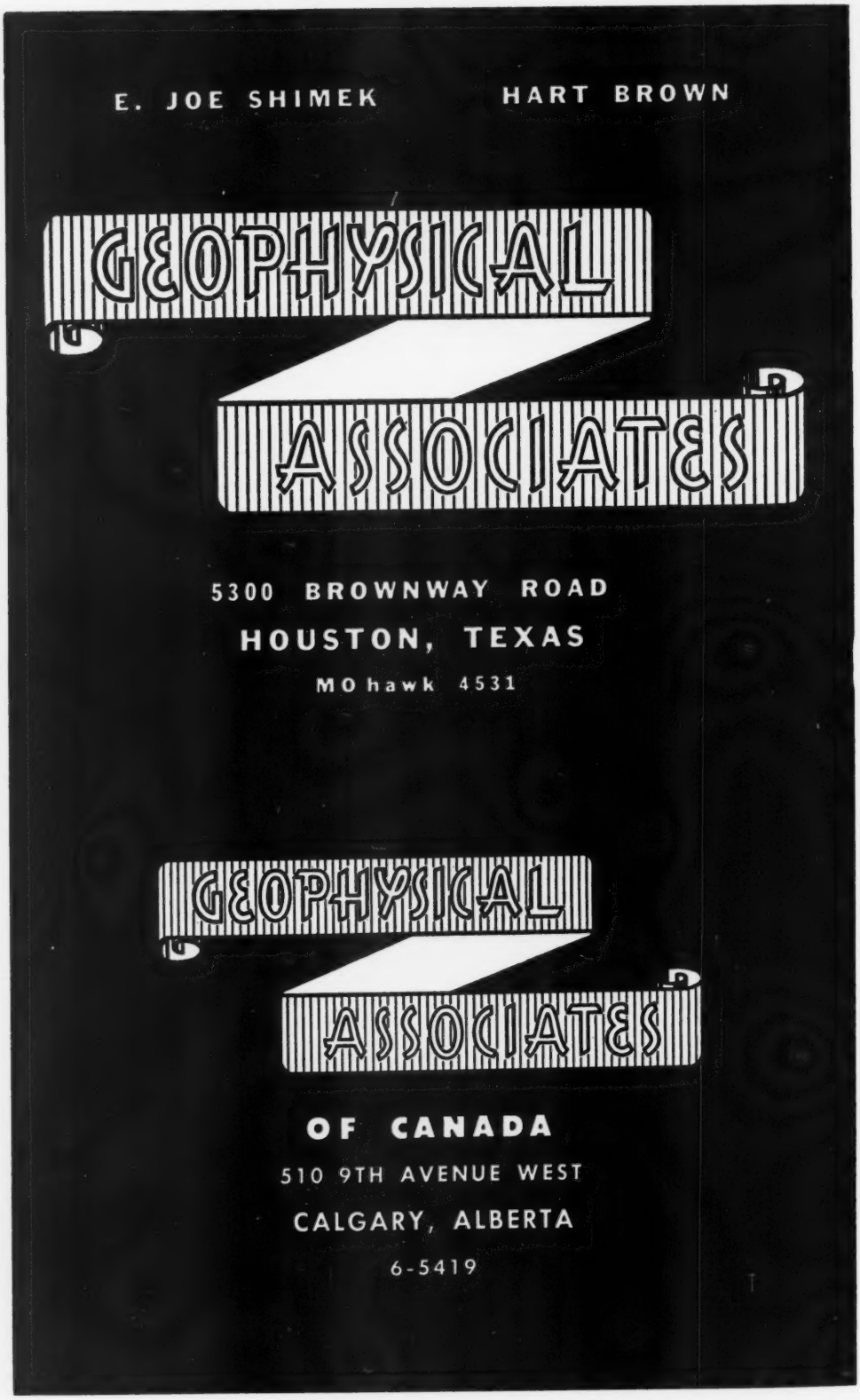
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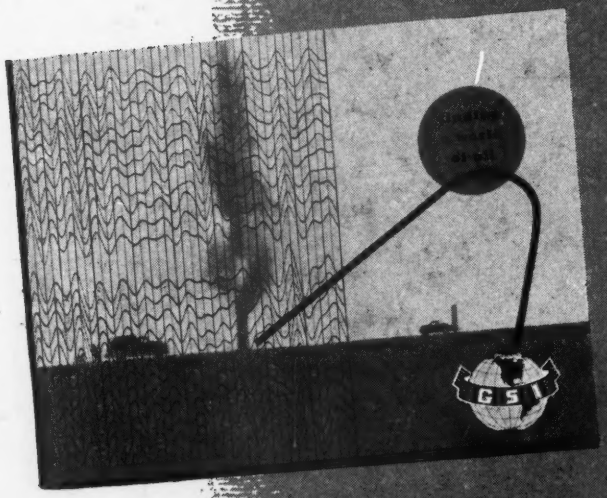

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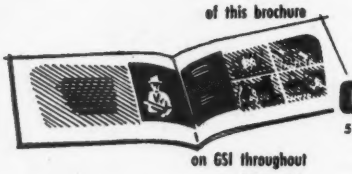

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